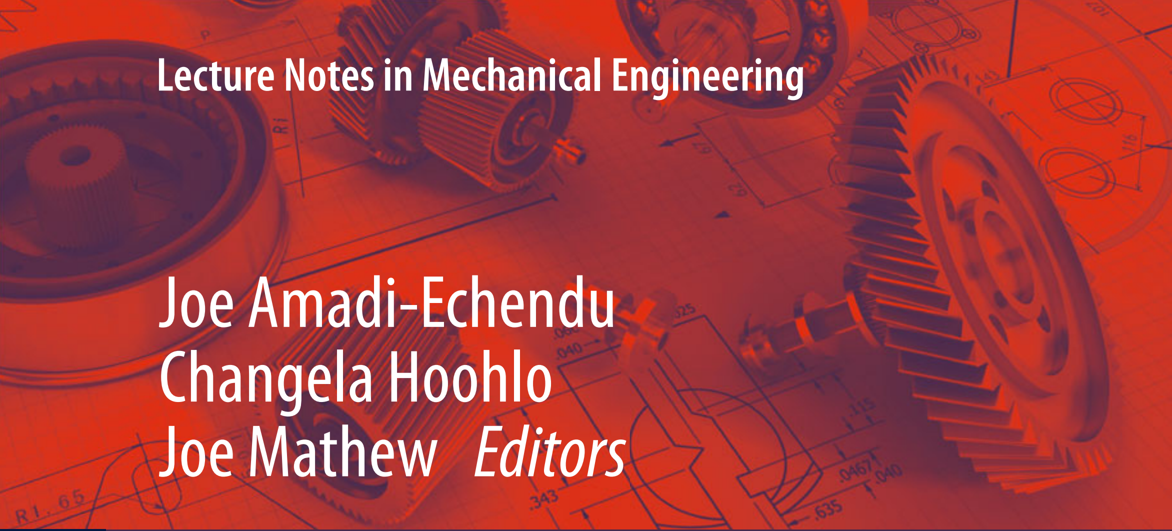

Lecture Notes in Mechanical Engineering

Joe Amadi-Echendu
Changela Hoohlo
Joe Mathew *Editors*

9th WCEAM Research Papers

Volume 1 Proceedings of 2014 World Congress on Engineering Asset Management

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ISSN 2195-4356 ISSN 2195-4364 (electronic)
Lecture Notes in Mechanical Engineering
ISBN 978-3-319-15535-7 ISBN 978-3-319-15536-4 (eBook)
DOI 10.1007/978-3-319-15536-4

Library of Congress Control Number: 2015932076

Springer Cham Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

Preface

Throughout history, engineering assets have provided the impetus, and continue to drive the advance of human civilization. Engineering assets make up our built environment, and include man-made physical artefacts like infrastructure, plant, equipment, hardware and software tools and systems, and are deployed across all industry sectors of human endeavour. Engineering assets not only improve almost every aspect of how we live but also, they enhance the joy of living by complementing, supplementing and directly replacing humans in numerous laborious and dangerous tasks. As we depend more and more on engineering assets to provide the means for enhancing our livelihoods, we must advertently manage engineering assets so that they sustain increased quality of life in a world of finite resources.

The 9th World Congress on Engineering Asset Management theme, “Towards Engineering Asset Management Body of Knowledge and Standards”, reinforces the excitement stirred by the release of ISO 5500x standards. On the one hand, the words ‘asset’ and ‘management’ are, respectively, broad and ubiquitous, and engineering assets are basically technologies that exist in the form of man-made tangible things. On the other hand, *engineering* and *technology* constitute *diadelphous* and *dicephalous* dualism, that is, of the same umbilical cord. Thus, as we grapple with what should constitute the body of knowledge for a subject matter that is cross-, multi-, and transdisciplinary, we prefer to name the field of endeavour, or the subject area as “Engineering Asset Management (EAM)”:

i. to minimize ambiguity that may be inherent in the term ‘physical assets’—in the sense that land and mineral resources are also ‘physical’;
ii. to provide a conventional academic home for studying, teaching and research in Engineering Asset Management.

With delegates from more than 18 countries, the 9th WCEAM programme featured:

- Research poster presentations
- 1 plenary presentation
- 4 keynote addresses
- 3 panel discussion sessions
- 4 seminar sessions
- 6 tutorial master classes
- 6 practitioner workshops
- 72 paper presentations
- 11 exhibitions
- ‘Madiba Magic’ tour
- Wildlife Game drive
- Memorable entertainment

December 2014

Joe Amadi-Echendu
Changela Hoohlo
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9th WCEAM Organization

Organizer
International Society of Engineering Asset Management (ISEAM) www.iseam.org

Hosts
Graduate School of Technology Management, University of Pretoria, City of Tshwane, South Africa

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The organizing committee for 9th WCEAM, ISEAM, and the Graduate School of Technology Management, University of Pretoria, acknowledge the partnership with ABSA Capital, South Africa; Anglo American Platinum, South Africa; City of Tshwane, South Africa; Council for Scientific and Industrial Research, South Africa; Eskom Generation, South Africa; Esri Inc., USA; National Department of Treasury, South Africa; National Research Foundation, South Africa; Passenger Rail Agency of South Africa, South African Bureau of Standards, and South Africa National Convention Bureau.

The organizing committee also recognizes special contributions received from representatives of the following organizations—Automotive Industry Development Centre, South Africa; National Department of Public Works, South Africa; Joy-global, South Africa; Stanlib Asset Management, South Africa; Asset Institute, Australia; Blue Australia; Queensland Audit Office, Australia; DSD-SAR, Hong Kong; Intelligent Maintenance Centre Cincinnati, USA; CIAM Stavanger, Norway; EPFL, Switzerland; Encada LLC, USA; PHM Society; and TWPL, UK.

9th WCEAM Theme, Tracks and Topics

Towards Engineering Asset Management Body of Knowledge

Tracks	Topics	Issues
EAM strategies	Investment	Custodianship, ownership and stewardship Asset acquisition planning Asset funding and financing options Valuation Private–public partnerships Private–private partnerships Product/service transformation (servitization) Outsourcing
	Operations and maintenance strategies	Utilisation, demand loading and forecasting Operational philosophy, planning and scheduling Maintenance planning, scheduling, and work execution
	Divestment and sustainability	Divestment options (i.e. alternative uses) Environmental impact, ecological footprint
Condition, risk and vulnerability	Operability, maintainability, reliability, availability Condition, risk and vulnerability assessments Diagnostics and failure mechanisms Prognostics Life-cycle decisions	Condition Useful life Remaining life Replacement, refurbishment, renewal, upgrade, etc.

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Tracks	Topics	Issues
EAM data and information	Asset register and data Information and knowledge management Asset performance indicators Performance measurement	Acquisition data Asset identification Accounting Utilization, value profile
Technologies and systems	Information and communication networks Enterprise resource planning systems Knowledge and project information systems Operational and safeguarding systems	Data and information integration Interchangeability, interoperability supply chain, logistics support
Standards and guidelines	Management systems ICT systems Engineering design and technical Accounting and financial Legal and legislative National/local guidelines	International standards Operating standards National and local guidelines
Case studies	Industry sectors, e.g. agriculture, manufacturing energy, mining general services, utilities telecommunications and transportation	Research and application in various sectors of public and private industry

9th WCEAM Review Process

Full paper submissions were required in the first instance, and 118 highly relevant papers were submitted from 21 countries. Following stringent submission instructions, all papers were rigorously subjected to double, and in some cases, triple-blind reviews. The authors were invited to indicate a category for their paper(s):

i. Category A—for a paper that describes 'innovative' research work and practical relevance;
ii. Category B—for a paper that describes good quality research work and practical relevance; and
iii. Category C—for a paper that provides practical insight into real asset management situations.

9*th WCEAM Research Papers Volume* 1 *Proceedings of* 2014 *World Congress on Engineering Asset Management* comprises papers selected based on

i. first round pre-Congress blind peer-review,
ii. second round presentations during the Congress; and
iii. third round editorial process.

The selected contributions have been organized as chapters into four parts:

i. Part I—Engineering Asset Management (EAM) Strategies (Chaps. 1–7)
ii. Part II—Condition, Risk and Vulnerability Assessments (Chaps. 8–18)
iii. Part III—EAM Technologies and Systems (Chaps. 19–28)
iv. Part IV—Case Studies (Chaps. 29–34)

This publication has benefited from advice provided to the authors during the reviews by the following international panel of reviewers:

Amy Trappey, National Tsing Hua University, Taiwan
Andy Tan, QUT Brisbane, Australia
Andy Koronios, University of South Australia
Basim Al-Najjar, Linnaeus University
Benoit Iung, CRAN—Nancy University

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As much as possible, comments and suggestions captured during the presentations were applied during the editorial selection of the contributions.

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Joe Amadi-Echendu is a registered professional Electrical/Electronic Engineer who commenced his career as an apprentice technician in a manufacturing plant, and currently serves as Professor of Engineering and Technology Management, Graduate School of Technology Management, University of Pretoria. Joe's professional career is underpinned by his doctoral research in digital signal processing, condition monitoring and diagnostic engineering management of physical plants and processes. He has worked in both industry and academia in management and senior positions, and his 32 years' experience and interests cover the broad fields of engineering and technology management with particular emphasis on the management of intellectual assets, as well as the management of engineering technologies manifesting as plants, equipment and infrastructure assets. Professor Joe is a registered Professional Engineer with continuing consulting experience spanning many public and private industry sectors. He is a Founding Director of the Institute of Engineering, Technology and Innovation Management (METI) at the University of Port Harcourt, a Founding Fellow of the International Society of Engineering Asset Management (ISEAM), and serves in a number of international scholarly and standards organizations. Professor Amadi-Echendu is a recipient of at least seven local and international awards, and continues to serve as first Editor-in-Chief of Springer's Engineering Asset Management Review Series.

Changela Hoohlo is a registered professional Civil Engineer with more than 23 years' experience in all aspects of infrastructure project development in both the public and private sectors. Dr. Hoohlo is the Managing Director of Dynacon Consulting, a company specializing in infrastructure project contract administration, execution, financing, management, packaging, rehabilitation and sourcing. Changela is a member of a number of private industry-based organizations, as well as external examiner for Master's degree research projects at universities.

Joe Mathew is a Mechanical Engineer with extensive experience in academic administration, research management and consulting. As Queensland University of Technology's (QUT) Head of School of Mechanical, Manufacturing and Medical Engineering, he led the successful bid to form the Australian National Cooperative Research Centre (CRC) for Integrated Engineering Asset Management (CIEAM) in 2003. Technically, Joe specializes in condition monitoring, and diagnostics and prognostics of machine systems. He is one of the two founders of the International Standards Organization's Committee on Condition Monitoring and Diagnostics (ISO TC 108/SC5), which he has chaired since 1996. He led the formation of the International Society of Engineering Asset Management (ISEAM) and the World Congress on Engineering Asset Management (WCEAM). He serves as Foundation Chair of ISEAM and General Chair of the WCEAM. Joe was recently appointed CEO of the newly founded Asset Institute based at QUT and has been the key facilitator behind the Institute's transition from a CRC.

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Part I
EAM Strategies

Market Risk Management in the Context of Engineering Asset Management

Eben Maré

Abstract Engineering asset management has a broad scope and covers a wide variety of areas. These would typically include general management, operations and production areas as well as financial aspects. It is essential to consider risk management aspects arising from asset management activities, in particular if we view financial assets of the firm as financial derivatives of our engineering assets. A coordinated strategic framework is required to ascertain Enterprise Risk Management. In this paper we focus on market risk aspects in the context of engineering asset management. We demonstrate the market risk process and note implementation requirements.

Keywords Engineering asset management · Enterprise risk management · Market risk quantification

1 Introduction

> There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we know we don't know. But there are also unknown unknowns. There are things we don't know we don't know (Rumsfeld 2002).

There are various definitions for engineering asset management (EAM) in the literature. There is, however, little uncertainty that EAM is conducted with the ultimate aim of positive economic utility expansion (i.e., creating profits). We are desirous to understand the overall total management of enterprise value resulting from the financial dimensions of our engineering assets (see, Amadi-Echendu et al. [3]). In this endeavour we need to heed the words above, noting the effects of various uncertain events on our enterprise.

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_1

> Banks (2002) notes: Risk, which can impact all areas of personal and corporate activity, can be defined as the uncertainty surrounding the outcome of future events. In order to manage and control risks – to reduce or contain possible losses caused by uncertain future event – firms should strive to use all available tools and approaches. By doing so they minimise the chance that unacceptable losses will occur.

Modern business faces a multitude of risks such as liquidity, operational, credit and market risks amongst others. Our aim in this paper is to discuss a market risk management framework within the context of EAM. The outline of the paper is as follows. In Sect. 2 we discuss the connection between EAM and financial aspects as seen in the literature. Section 3 is devoted to a discussion on traditional market risks while Sect. 4 describes the full risk management process. Section 5 is devoted to implementation issues within the EAM setting. We conclude in Sect. 6.

2 Engineering Asset Management and Enterprise Risk Management

Amadi-Echendu et al. [3] note that the definitions of EAM tend to be broad in scope, typically covering general management, operations, financial and human capital elements. In earlier work [1], the authors emphasize the importance of considering engineering asset management holistically within the overall business context. The view is echoed in [28], and further work in [2] emphasized the need to embrace holistic thinking. Thorpe [25] notes the need for economic thinking while [18] emphasize the EAM life-cycle, and [4] considers risk management and quantification for EAM decision making.

There is acknowledgement [15] that effective asset management requires an interdisciplinary approach with synergies between accounting, engineering, finance, humanities, logistics and information systems. Badurdeen et al. [5] emphasize that sustainability has become a key driver in the operations of companies. To ensure a competitive approach they note the need to model risk and enhance decision support to enhance returns. In the modern financial environment we frequently encounter this synergetic approach under the term Enterprise Risk Management (ERM), see, for example, [11], and [20], as well as [23]. ERM typically calls for a framework wherein all risks are assembled and strategically coordinated [26].

The paper by Amadi-Echendu et al. [3] differentiates between engineering asset objects and financial asset objects. In their view, financial assets exist and have value as financial derivatives of engineering assets. This point of view is extremely important for our discussion. We will discuss a variety of market related risks which could affect the financial asset objects of a firm.

3 Traditional Market Risk

Market risk arises by virtue of changes to our enterprise value (typically income statement or balance sheet related) as a consequence of changes in the values of traded securities. These would typically be:

i. Equities,
ii. Foreign currency (or currencies),
iii. Interest rate(s)—nominal and/or real,
iv. Commodities,
v. Credit spreads,
vi. Energy prices,
vii. Changes in volatility and correlations of the above instruments.

In a typical financial institution these changes could be as a consequence of direct exposures, i.e., physical holdings in bonds, equities or foreign currency, for example. The institution could also have exposure to the above securities by virtue of synthetic derivatives resulting from its business activities to hedge structured products or facilitate corporate hedging schemes, for example. Typical examples of bank client facilitation would be interest rate swaps, commodity swaps, foreign exchange basis swaps, equity options and futures as well as corporate bonds and credit default swaps.

Financial institutions could, however, also carry indirect exposures to changes in the above securities. An example could be deterioration of the credit quality of a bank's mortgage loan book as a result of rising interest rates. An asset management company, for example, typically levies its fees on the assets under its management—a crash or bear market in equities would reduce the institution's fee income dramatically. Indirect exposures could include so-called real options as well; see, for example [22].

In the setting described in [3], we will obviously aim to discover the effect of market related variable changes on our financial asset objects. These can be viewed as derivatives and the theory of conditional asset and liability modeling would apply. Hence, foreign exchange adjustments on equipment imports, changes in the prices of commodity used as inputs to be processed by engineering assets, increased borrowing costs resulting from higher interest rates or decreased credit ratings as well as corrosive effects of inflation constitute examples of direct market risks to our financial asset objects.

4 Risk Management Process

Risk management is a total enterprise contained activity. We will discuss the following key elements of the process.

i. Risk identification,
ii. Risk measurement,
iii. Monitoring,
iv. Control,
v. Testing and evaluation.

Let us elaborate on these process elements below. See, for example, [7, 9, 21, 24, 27].

4.1 Risk Identification

We need to examine all aspects of our business to understand the consequences of changes in market variables—these could be direct or indirect. We would critically examine our regular management accounts and ensure a deep understanding of our income statement and balance sheet. We would look at our regular budgeting process and overlay what-if scenarios to ensure an understanding of the functional relationship between our enterprise value and direct or indirect changes in market variables. This should be seen as an ongoing process [7].

4.2 Risk Measurement

After we have identified sources of risk we need to quantify the extent of the risks involved. Risk quantification is typically associated with some risk measurement metric which could be based on statistical or analytical methods or scenario analyses. At a basic level we could attempt to describe our risk exposure in terms of an equivalent spot position, e.g., an equivalent nominal loan exposure amount. If a company is exposed to a set of risks which are very similar we could construct a proxy to perform a 'back-of-the-envelope' risk calculation. An example would be to approximate a basket of equities by an index. The advantage of such an approach is simplicity and yielding an 'effective' position which management relates to. The obvious disadvantage is that we are making some serious assumptions regarding basis risks between different (but related) positions.

In a typical financial institution, risk quantification is usually done through several risk measurement metrics ranging from simple spot equivalent positions to so-called value-at-risk (VaR) and stress testing; see [12]. VaR is a measure of the loss on a portfolio that will not be exceeded over a holding period within a certain confidence level. More formally, VaR has been defined as the loss (stated with a specified probability) from adverse market movements over a fixed time horizon, assuming the portfolio is not managed during this time. Hence VaR is measured as the lower percentile of a distribution for theoretical profit and loss that arises from possible movements of the market risk factors over a fixed time horizon. Stress testing looks at the effect of significant changes in market variables to our financial exposures—an example could be to see how much we make/lose if the exchange rate depreciates by 20 % overnight. Stress tests are very useful to identify risks [6].

4.3 Risk Monitoring and Control

After we have calculated some risk-measure associated with an identified risk it means that we have a sense of the economic damage that could be caused as a result of that risk. We should judge against that the economic benefit from having the risk —such as the amount of profit or other advantage that we would derive. Realistically, we would not want unbounded amounts of any risk and would impose limits to control these risks. It is important therefore to ensure that we set our controls (limits) to be reflective of the identified risks and that these accurately control the exposure that will ultimately feed through to our income statement. Our process is therefore to monitor the measured risks against limits on a periodic basis and to ensure the correct level of control of our risks.

4.4 Testing

Market risk management is most successful in an environment where risks are transparently discussed and completely understood. It is extremely important to dissect risk and to understand the impact thereof on our income statement, balance sheet and enterprise value. We also need to understand whether we are adequately compensated for risks that we carry. We need to monitor the full risk measurement and management process continually to ensure that we have captured all risks and to test the validity of our assumptions used to derive our understanding and measurements of risks.

We started by investigating the effect of risks to our income statement—it is therefore only fair to balance back to the income statement in the sense that observed market moves applied to our calculated sensitivities should balance to our observed profit/loss numbers. If this is not the case we are missing part of our exposures! By regular testing we ensure that we do not ignore important risks by leaving them undetected or wrongly view them as immaterial [24]. The 2008 credit crisis emphasized the need for continual risk model testing; see [26], as well as [19], and [13].

5 Implementation Issues: Requirements and Challenges

Implementation of a market risk measurement and management system in a typical EAM setting could be challenging from an organisational and technological perspective. We provide a brief discussion of the requirements to implement the process described in the previous section. The approach we describe would extend to other risk types in the organisation also, examples being liquidity, credit and operational risks.

5.1 Risk Philosophy

From an enterprise risk perspective, firms need to establish a view of risk tolerance. Firms need to determine how to attribute resources to manage risks; see [7]. An essential part of the philosophy entails a firm wide exploration whether risk is an integral part of the business of a by-product which needs to be eliminated or minimised; see also [10]. Creating a risk policy requires balancing of many forces. Amadi-Echendu et al. [3] notes that one of the requirements for broad based EAM is organisational generality: "EAM takes place at all levels of the organisation, from direct contact with the asset to strategic interactions that take place in the boardroom". In this sense EAM is directly connected to risk management.

5.2 Information Systems

Measuring and understanding our exposures require full information of our engineering assets and liabilities. Amadi-Echendu et al. [3] notes the need for an information system which provides data on physical and financial conditions of assets, while [1] discussed an accounting system as the basis of an EAM information system in this context. Poor data quality would typically be the most significant impediment [28], see also [16], and [17].

From a risk measurement perspective we would typically translate cash flows obtained from the accounting system into risk sensitivities taking the discussion in Sect. 3 into account [12]. In the EAM environment we have complex assets but low volumes; this is fortunate as it allows for a deeper analysis of the risk sensitivities of specific assets.

5.3 Management Action

Information flow is of paramount importance, and [24] notes: "In a typical company, the role of risk management is to identify and evaluate the risks faced by the firm". Risk measures are only meaningful if an enterprise is willing to use these to reduce risk within the agreed tolerance of overall risk policy. It is essential that risk measures be understood and treated as real exposures and not just "nice to have" numbers.

Risk management systems can break down as a consequence of inappropriate risk metrics, mis-measurement of known risks, not taking known risks into account, inappropriate risk communication to management and failure in monitoring and managing risks [24]. Management need to ensure that appropriate actions are taken to ensure a working risk capability. Risk management is a culture; a coordinated risk management framework ensures that risk is managed at all levels in the firm. It is therefore imperative that risk management actions be understood at all levels of the firm [8].

6 Conclusion

Amadi-Echendu et al. [3] noted that EAM is multi-disciplinary requiring skills from a multitude of disciplines including traditional engineering, information technology, economics and management. They noted the need for information systems to capture data to support decision making. We have shown that this requirement is of vital importance for the risk function too. "It is no longer sufficient to consider asset management as simply the maintenance of an asset, but rather as a holistic approach to the management of asset, incorporating elements such as strategy, risk measurement, safety, environment and human factors" [14].

Risk management is best implemented by professionals who are subject area experts with an in-depth understanding of the risks associated with assets. In that sense, we are broadening the traditional scope of EAM. To ensure an overall coordinated risk framework we need to embrace an ERM framework.

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Application of a Performance-driven Total Cost of Ownership (TCO) Evaluation Model for Physical Asset Management

Irene Roda and Marco Garetti

Abstract The core concept of this paper is total cost of ownership (TCO) of industrial asset and its relevance in supporting decision making if properly evaluated through the analysis of the technical performances of the asset. The paper is based on a framework that systematizes benefits and potential applications of TCO for different kind of stakeholders at different stages of the life cycle of the asset, supporting different kind of decisions. The aim is to present an experimental case study that has been implemented in order to show the empirical evidence of what is in the framework by focusing on one of the primary companies in the chemical industry in Italy. The application proposes a modeling approach for trying to overcome one main gap that still subsists when referring to TCO models that is that most of the existing ones lack of the integration of technical performances evaluations into the cost models or are based on very limiting hypothesis. In this paper a comprehensive methodology for the evaluation of Total Cost of Ownership of industrial assets that has being developed within a research activity carried out at the Department of Management, Economics and Industrial Engineering of Politecnico di Milano is presented.

Keywords Asset management performance · Total cost of ownership · Asset performance measurement

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_2

1 Introduction

In order to meet the challenges of global competition and changing market conditions, production companies need to adopt an asset management strategy and system to sustain or improve the life cycle profits of the original investment [11, 12, 18]. With this regard, one of the challenges in the physical asset management field is to keep a life cycle perspective whenever a decision is taken both for acquisition or configuration and management actions on any asset. Through this perspective, it is essential to improve the quantification process of costs, in order to be able to evaluate the total cost of operating a production system throughout its life cycle (i.e., the so called Total Cost of Ownership (TCO)) as supporting evidence that allows informed decision-making [27].

More in detail, this work refers to the concept of TCO intended as the actual value of the sum of all significant costs involved for acquiring, owning and operating physical assets over their useful lives [37]. TCO is strictly related to the concept of Life Cycle Cost (LCC) and they are often used without distinction in literature. The widely shared idea is that TCO provides a selected perspective on LCC. In contrast to LCC, it focuses on the ownership perspective of the considered object and all the costs that occur during the course of ownership [19]. Moreover [8] and other authors later on, used it with a more strategic connotation, giving to TCO the meaning of a supporting information for strategic choices regarding both investment decisions and operational strategies.

It is widely accepted in the academic literature [32] that TCO should be an integral part of an asset management strategy and the same is assessed by the ISO 55000 series of standards for asset management. In particular, the latter puts into evidence the relevance of being able to quantify the TCO of an asset, being it an industrial system or a single equipment, and it is indicated that: "[…] Life cycle cost, which may include capital expenditure, financing and operational costs, should be considered in the decision-making process. […] When making asset management decisions, the organization should use a methodology that evaluates options of investing in new or existing assets, or operational alternatives" [13, Sect. 6.2.2.4]. On the industry side, companies are more and more acknowledging that a TCO model can represent a reliable economic-sound support for taking decisions and conveying the information it represents to both internal and external (costumers/suppliers) stakeholders [1].

This paper refers to the framework (Table 1) that the authors developed based on an extensive literature review aiming at highlighting the benefits of the adoption of a TCO model in decision making support for asset management [28]. Developing the framework, three main dimensions have been identified:

a. type of stakeholder: given the meaning itself of TCO, it is evident that asset users (asset owners/managers) are the main stakeholders; nevertheless asset providers (asset builders/manufacturers) have also interest in evaluating the TCO of assets they build/sell.

Table 1 Framework of benefits of TCO adoption in decision making for asset providers/users

	Asset provider		Asset user	
	Configuration	Management	Configuration	Management
BOL	Evaluation of project alternatives	Communicating value to the customer and selling support	Evaluation of design alternatives offered by a provider	Suppliers and tenders evaluation and selection
	Comparison and optimization of design alternatives	Propose to the clients specific design solutions		Maintenance service contract evaluation
	Components/equipment procurement and construction alternatives evaluation	Pricing		Investment, budget planning, cost control
	Spare parts requirements estimation	Contracting maintenance services provision		
MOL	Proposal of re-configuration solutions	Maintenance service provision offering	Reconfiguration decisions	Maintenance scheduling and management
		Spare parts provision offering	WIP sizing	Repair level analysis
				Asset utilization and production strategies
EOL	Proposal of reconfiguration for EoL optimization	Evaluation and proposal of rehabilitation strategies	Reuse strategies for components/machines	Evaluation of rehabilitation strategies

b. type of supported decision: a TCO model has got potentiality to support different kinds of decisions and in the framework two main categories have been identified:

   (i) configuration decisions and
   (ii) management decisions.

c. phase of the life cycle: TCO analysis can be carried out in any and all phases of an asset's life cycle (Beginning of Life (BOL), Middle of Life (MOL) and End of Life (EOL)) to provide input to decision makers.

The framework shows which benefits a TCO model can bring to each of the two types of stakeholder at each lifecycle phase by supporting different kinds of decisions (configuration or management decisions).

2 Problem Statement and Objective

Even if it clearly emerges from the literature that TCO has got positive effect in supporting decision making for asset management; however, many limitations exist up to day. The main issue is that most of the TCO methods developed so far only consider the cost but neglect the performance of the system, which has significant limitations [6]. A crucial point in order to understand the applicability of a TCO model for supporting physical asset management is that the evaluation criteria for the costs elements definition should encompass not only all incurring cost elements along the asset life cycle but also system performance characteristics, like system availability, in upfront decisions for achieving the lowest long term cost of ownership [8, 17, 37].

Indeed, some main issues should be considered when approaching the TCO evaluation of a production system as a support for decision making:

i. a large number of variables directly and indirectly affect the real cost items and are affected by uncertainty in their future evolution (e.g. inflation, rise/decrease of cost of energy, cost of raw material, cost of labor, budget limitations, etc.) [9, 26];
ii. the evolution of asset behavior in the future is difficult to predict (e.g. aging of assets, failures occurrence, performance decay) and 'infinitely reliable' components or systems do not exist [31];
iii. complex relationships in the assets intensive system dynamics, due to the presence of many coupled degrees of freedom, make it not easy to understand the effects of local causes on the global scale [38];
iv. conventional cost accounting fails to provide manufacturers with reliable cost information due to the inability of counting the so-called invisible and, in particular, intangible costs, and thus there is inaccuracy in calculating total costs [7].

It is evident that additional research is required to develop better TCO models to quantify the risks, costs, and benefits associated with physical assets including uncertainties and system state and performance evaluations to generate informed decisions [33]. The objective of this paper is to present a comprehensive methodology for the evaluation of the TCO of industrial assets that has being developed within a research activity carried out at the Department of Management, Economics and Industrial Engineering of Politecnico di Milano. The methodology is based on an integrated modelling approach putting together a technical model for the evaluation of the technical performances of the asset over its lifecycle (by accordingly generating the asset failure, repair and operation events) and a cost model for evaluating the final cost breakdown and the corresponding TCO calculation (Fig. 1). An industrial application case study has been implemented and first experimental findings of developed methodology are presented showing the relevance and potentialities of such approach for companies.

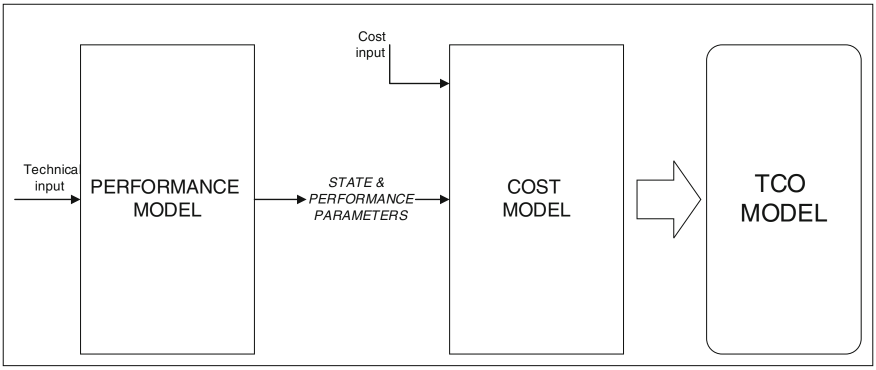

Fig. 1 Concept of integrated TCO evaluation model

3 Performance-Driven TCO Evaluation Methodology

The TCO methodology that is presented in this paper, is based on the idea that only by the integration of a performance model and a cost model is it possible to develop a reliable TCO model to support strategic decision-making (Fig. 1).

The underlying assumption is that proper system modeling has to be introduced for availability, maintainability and operation and that it must be integrated with a cost model for economic evaluations.

Cost model:
Whilst there is general agreement that all costs occurring along the life cycle of an asset should be included in the related TCO model, opinion varies as to their precise identification [37]. Several cost models have been proposed in literature and different ways to categorize the main cost items can be found. Some models group cost items depending on the life cycle phases of the asset, others refer to the two main categories CAPEX and OPEX. In spite of these different categorization approaches, in the end the detailed costs items list will depend upon the particular system under consideration and a cost break down structure (CBS) approach is commonly adopted [4, 17]. The important point is that the cost structure must be designed so that the analyst can perform the necessary TCO analysis and trade-offs to suit the objectives of the project and the company concerned [37]. Table 2 shows the CBS that has been defined for the specific case study that is presented in Sect. 4. The specific cost model includes the main cost items that are usually considered by a manufacturing company for evaluating different design solutions for production systems.

A relevant issue that must be taken into account and that is mostly undervalued in practice, is the need to include those cost elements that depend on the performance of the system within the cost model. For example, it has to be considered that when an asset fails, the cost is not limited to the cost of repair or replacement (in terms of manpower and material), but the money lost because the asset is out of service must be included as well [35]. The same is valid for other performance

Table 2 Cost categories in TCO cost model

Summary of costs per category	
CAPEX	OPEX
1. Purchasing price	7. Energy cost
2. Installation fixed cost	8. Line operators labor cost
3. Civil works cost	9. Maintenance visible cost
4. Commissioning cost	9.1. Maintenance personnel cost
5. Extra cost	9.2. Spare parts cost
6. Installation labor cost	10. Losses related costs
	10.1. *Management losses costs*
	10.2. *Corrective maintenance downtime losses costs*
	10.3. *Speed losses costs*
	10.4. *Non-quality costs*
	10.5. *Labor Savings*
	END OF LIFE COSTS AND SAVINGS
	11. Decommissioning costs

losses consequences (e.g., quality losses, speed losses etc.). All these aspects must be considered within a complete TCO model, hence it is necessary to evaluate and to quantify factors that allow predicting the form in which the production processes can lose their operational continuity due to events of accidental failures and to evaluate the impact in the costs that the failures cause in security, environment, operations and production [26, 36].

To this regard, a widely used performance measure in the manufacturing industry is overall equipment effectiveness (OEE) originally introduced by [25, 14]. It is clear that for making asset management decisions it is important to have a thorough insight into all involved costs and their impacts on the profit and competitiveness. Managers need to consider the trade-offs between the amount of investment and its impact on the OEE and TCO becomes an indicator required for competitiveness analysis [13]. The following Fig. 2 shows which are the losses that have been considered into the cost model in the methodology herein proposed, by referring to OEE. The identified losses (availability, performance and quality losses) lead to specific cost items in the OPEX category of the cost model (Table 2, cost items under category 10) and they must be evaluated through a performance model as it is detailed in next section.

Performance Model:
As assessed above, system state and performance evaluation is an essential step that needs to be developed to feed with the proper inputs the cost model, hence to evaluate the real TCO referring to an asset.

Obviously in complex systems, OEE should be calculated at system level, by correctly considering the result of dynamic interactions among various system components (i.e. individual assets). This issue has been identified by [15, 23, 24]; and the latters introduced the term overall throughput effectiveness (OTE) as a

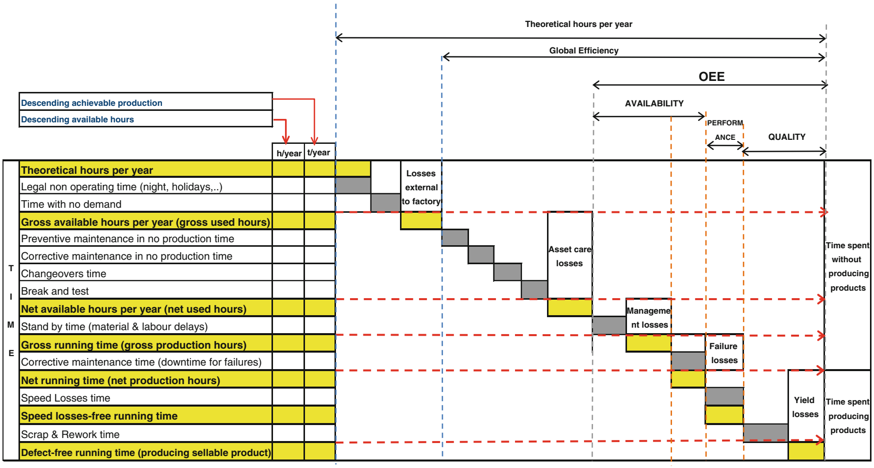

Fig. 2 Outline of losses and OEE calculation scheme

factory-level version of OEE that takes the dependability of equipment into account. Some approaches have been proposed in literature in order to try and face the quantification of costs related to system unavailability. On one hand, the most traditional approach is to use ex-post analysis as a calculation based on historical or actual data; applying the traditional RAM analysis based on statistical calculations or probabilistic fittings. On the other hand, great potentialities are added by applying ex-ante estimation aiming at a static or dynamic prediction of total costs through estimated behavior over the life cycle [34]. Within this second perspective, some works have been proposed in literature suggesting the use of stochastic point process [16, 19, 26] and some others propose the use of simulation based on the Monte Carlo technique [10, 30, 33]. In this work, the stochastic simulation is proposed for modeling the casual nature of stochastic phenomena and the Reliability Block Diagram (RBD) logic is used to express interdependencies among events thus evaluating how individual events impact over the whole system (Fig. 3).

The Monte-Carlo method is used for generating random events relying on the statistical distribution functions of the time before failure (TBF) and time to repair (TTR) variables given as input values at component level. Both failures modes and stops of the system related to other reasons (such as operations problems) can be considered. Using the simulation technique, the system behavior can be generated in a series of random iterations by calculating as a final result, a statistical estimate value of operational availability and OTE for the complete system. One of the main disadvantages of the use of simulation is the high effort that it requires for making the system model and data preparation [17]. To this regard, new approaches are introducing the use of some conventional modeling techniques such RBD for simulation purposes [20, 21, 29]. In fact the RBD logic has the advantages of giving a systemic, integrated and very compact view of the system with a bottom-up perspective while keeping an easy implementation approach. In order to ease

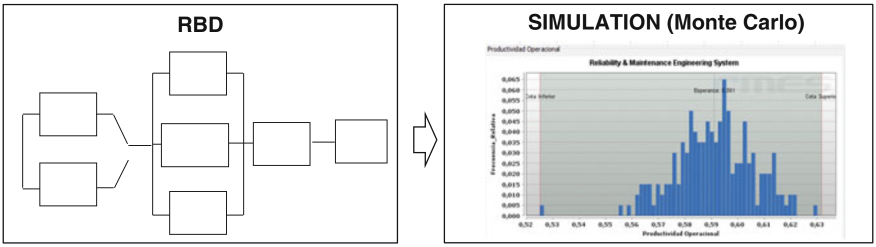

Fig. 3 Tools for the performance evaluation model

application, these concepts have been embodied recently in several software based tools for asset management which use simulation (such as for example Availability Workbench™ by ARMS reliability; Relex or R-MES Project©). Within this approach, aspects that go beyond the pure unavailability evaluation determined by asset failures can be considered such as production losses due to system performance or quality reduction.

This approach has been adopted in the proposed model for the evaluation of technical performances. The performance model allows evaluating the OTE of a system by taking into account assets behavior and dependability during equipment lifecycle. Such information is a relevant input for the evaluation of the OPEX cost components within the cost model (Table 2).

After the evaluation of the costs elements using the outputs of the simulation where needed, the sum of all costs can be actualized through the evaluation of the Net Present Value (NPV) or the Average Annual Cost of the TCO.

4 Application Case

4.1 Background

The performance-driven TCO calculation methodology has been applied in a case study regarding a primary chemical company in Italy, particularly concerning an industrial line for rubber production. Next Fig. 4 shows the basic process flow-sheet and the main equipment composing the plant section under analysis. The main objective of the case study is to apply the developed TCO evaluation methodology to prove its potentialities for supporting decision making.

Basing on the framework presented in Sect. 1, the methodology is applied by the *user's* perspective (owner and manager of the plant) dealing with the Middle of Life phase of its asset. The main potentialities expected from the evaluation of the TCO by the plant management are to support re-configuration choices through an economic quantification of the effect of technical changes in the plant. Hence the focus is on reconfiguration decisions/new acquisition investments.

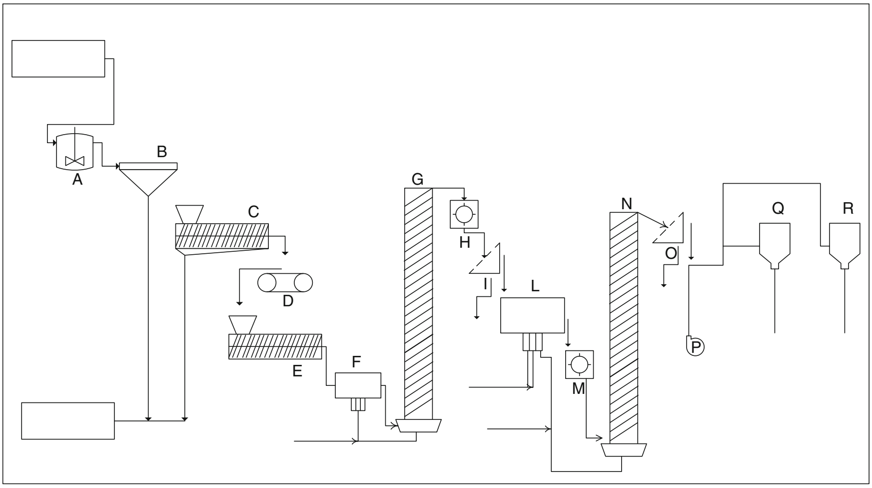

Fig. 4 The case-study production line

4.2 TCO Evaluation Procedure

The case is based on the use of the TCO evaluation methodology that has been presented above based on the cost model and performance model. In particular, the following steps have been developed for the application case.

Performance evaluation:

Step 1. Process understanding and system's components identification.
Step 2. Identification of failures modes or stop causes of each component.
Step 3. Reliability, maintanability and operation data acquisition (TBF and TTR).
Step 4. Modeling of the as-is system through RBD logic.
Step 5. Simulation (Monte Carlo).
Step 6. Technical performance calculation of the system.

On the basis of the given situation, 156 equipments have been put in the model and simulation runs (200 runs) were conducted in order to calculate the operational availability and OTE of the as-is situation over a time span of 5 years.[1] Such data was used as one of the inputs for the following cost modelling phase.

Cost evaluation:

Step 7. Cost model setting (Table 2).
Step 8–9. Cost data acquisition and Calculation of TCO.

[1] The reliability oriented engineering software R-MES Project© (Reliability Maintenance Engineering System Project) is used for performing the above mentioned modelling and calculation steps from 4 to 6.

Table 3 Results of OEE improvements in the investigated scenarios

	Scenario A	Scenario B	Scenario C
Delta OEE	+4.52 %	+0.73 %	+2.58 %

After evaluating the TCO for the as-is situation of the plant, a number of alternative scenarios has been defined (configuration/management alternatives) and the corresponding performance and cost models have been developed, thus allowing the calculation of the related TCO values.

4.3 Analysis of Alternative Scenarios

The implementation of the methodology resulted for the company as a useful approach in order to identify and support re-configuration decisions. The company identified three main potential alternative configuration scenarios of the production line and the methodology allowed evaluating the benefits in term of savings along the lifecycle of the system by the estimation of the differential TCO.

More in detail, the scenarios that have been proposed by the company asset managers for comparative evaluations are the following:

- Scenario A: the installation of a second machine of type E to be kept in stand-by with the already existing one;
- Scenario B: the disposal of the mechanical transport machine N and its substitution with a pneumatic transport system;
- Scenario C: The installation of three more screens in stand-by to the existing ones.

After implementing the methodology for the as-is situation and the three alterative ones, the technical outputs in terms of OEE (that are showed in Table 3) have been used to make the economic evaluation by combining them with the related cost inputs.

In particular, for each scenario, the differential costs and savings with respect to the as-is situation have been considered (such as, energy consumption, acquisition and installation costs, end of life disposal cost for the new equipment etc.), as well as the additional margin resulting from the increase in production volume.

After establishing a lifetime period for the evaluation of the various scenarios, the TCO cost calculation model allowed the company estimating the money cash-flow over the asset lifecycle and the payback time related to the investment required by each scenario. These data are not presented due to confidentiality reasons, however the results were very promising and attracted the attention of the company management asking for a more detailed estimation work.

4.4 Benefits and Limitations

After the case was developed and results generated, the plant management confirmed the usefulness of the model as a tool for supporting investment decisions by proving the return of an investment taking into account the life of the asset and its performance along it, going beyond the pure acquisition cost. The use of RAMS modeling techniques combined with Monte Carlo simulation engine provided a fast way to evaluate trade-offs among availability and redundancy. It resulted that performance analysis and reliability engineering are fundamental for financial and economic evaluations referring to capital-intensive asset systems. During the development of the case some criticalities emerged that need to be overcome in the future. In particular, the main limit was found at the data acquisition step. In fact, data regarding the past failures and repair events where spread among different sources and not complete to be used. This limit was overcome through the use of estimations asked to the plant experts of TBF and TTR values. The estimations allowed building triangular distributions for the two variables for each component to be used for the simulation. Anyways, it is evident that a reliable and complete historical data base would have made the calculations more precise through a fitting of the distributions over the real data.

5 Conclusions

TCO is seen a useful indication for guiding asset managers in the decision making process by companies and the main value is that it is a synthetic economic value including in itself a lifecycle vision and technical evaluations. TCO can be used as a management decision tool for harmonizing the never ending conflicts by focusing on facts, money, and time [5] and, if properly estimated it does represent a competitive advantage for companies.

Up to day, there are still a number of difficulties that limit a TCO model widespread adoption by industry and there is no single model that has been accepted as a standard. As it is pointed out by [1] the desire to implement life cycle costing was much talked about but little practiced. This can be attributed to several major obstacles which also emerged through the application case: (i) absence of a database and systematic approach to collect and analyze the significant amount of information generated over the life of projects [37], (ii) general lack inside the organizations of the adequate consideration of the entire asset life cycle that requires inter-functional cooperation and alignment [2, 3, 22], (iii) establishment of the more appropriate modelling approach for evaluating the technical performances of the asset over its lifecycle by accordingly generating the asset failure, repair and operation events.

The research work presented in this paper is following these issues moving in the direction of integrating technical performance and cost models so to be able to develop a realistic evaluation of the TCO of an asset over its estimated lifecycle. By using simulation together with RBD modeling of the system under study, allows to easily evaluate the technical performances of production systems in a computer environment.

On the other hand, the use of an appropriate cost model can support management in a decision making process which is oriented to the whole asset life cycle. This approach allows combining the reliability engineering concept to the economic and financial evaluation of investments translating them into the money-language which is essential to make the connection between asset management and profitability. Future research must include in the models also intangibles problems that are not necessarily related to production losses, but that lead to costs for the company. Moreover, more case studies may be developed to make the methodology generalizable.

Acknowledgments This research work has taken advantage from the application of TCO modelling methodology in an industrial case-study, hosted in the production premises of ENI Versalis in Ravenna (Italy). Many thanks are due to Mr. Saverio Albanese for his trusting in this research topic and to the Versalis Ravenna crew for their kind and passionate support.

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Government Entity Contribution to an Effective Partnership Privatisation

David Mills

Abstract The partnership form of privatisation is increasingly being used, in particular to carry out complex and evolving bundles of services. These have not previously been privatised because of incomplete contracts and contract management difficulties. Improved performance of the government entity as contract administrator and member of the partnership is crucial to modern service delivery expectations yet the privatisation literature has focused on other aspects of partnerships leaving the understanding of factors impacting the effectiveness of the government entity underdeveloped. This paper proposes the development of knowledge as to the range of factors which impact the effectiveness of the government entity. There is limited data available as to the operation of trust in the partnership relationship, and as to the capability of a range of privatisation forms to achieve stewardship of infrastructure. This research will utilise the findings from that research to build a tentative framework which will be utilised in staged research interrogating first the privatisation literature and then the literature of other disciplines and sectors. The combined data will be analysed to provide government and practitioners such as government entity CEO's with a complete listing of the operation of the factors which impact the effectiveness of the government entity in contributing to improved service delivery.

Keywords Public-private partnership · Asset management contracts · Asset service delivery

1 Introduction

The use of various forms of privatisation by government has increased significantly since the 1980s as governments seek to access the skills, expertise and funding of the private sector [11, 15]. The partnership form of privatisation is increasingly

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_3

being used, in particular to carry out complex and evolving bundles of services [1] which have not previously been privatised.

Some services had not been privatised because of the practical problems which lie at the heart of the contractual model, i.e. the difficulties faced by governments in clearly specifying what they want from contractors (incomplete contracts), monitoring whether they get it, and in replacing contractors who perform unsatisfactorily [7, 12, 16]. Now governments subject to intense pressures to be financially sustainable and to improve service delivery are reapplying the contestability strategy [14, 15] extending privatization into the activities previously judged difficult to privatise.

The privatisation literature has focused on the design of those “partnerships” targeted at accessing the funding and expertise of the private sector to construct and/or operate infrastructure [6], typically Private Finance Initiatives (PFI) or Public Private Partnerships (PPP). Less attention has been given to partnerships which are formed to carry out ongoing activities such as operations and maintenance or the delivery of services. The literature traverses the configuration and benefits of models of partnership, the joint venture and the alliance [13] giving particular attention to the role of the private sector participants. However, only limited attention is given to the role of the government entity, its configuration and staff arrangements.

Yet the partnership form of privatisation is distinguished from other forms of privatisation, such as classical contracts or the Build Own Operate Transfer (BOOT) form, by substantial involvement of the government entity. The role and scope of the government entity goes beyond that of contract management to include active collaboration and mixing with partnership members [18]. This mixing occurs between technical and service staff, executives and governance board members. Collectively, partnership staff are then required to handle the more difficult public administration activities, those characterised by uncertainty and complexity [1]. The question then is whether the government entity and its staff will be successful in contributing to improved service delivery through the partnership.

In Australia, a number of privatisations conducted by government entities with deep experience, typically engineering, in contracting with the private sector have failed. It follows then that government entities not experienced in privatisation are highly likely to not have the capabilities required for the partnership role.

The question then is: “What must be done by governments to ensure that each entity and its staff can achieve the objectives of the privatisation partnership?”

If this research were able to provide evidence or proposals as to how Governments and CEO’s of government entities might configure the structural and staffing arrangements of the entity then it is highly possible that the objective of the privatisation i.e. improved service delivery, will be achieved.

There is some evidence [1] as to the types of factors and issues which government must address when configuring the partnership, and in turn participating in the ongoing partnership. This paper will explore the strategy of using that evidence to set the likely scope of future research and to illustrate the benefit of knowledge regarding the government entity.

The focus of this research will be partnerships between a government organisation and a private company or not-for-profit organisation for the provision of ongoing services which previously have been produced internally by government. This paper will first explore the literature as to the range of modern models of government/non-government partnerships. Second for these partnership models the knowledge available as to the capabilities required of the government entity and the skills required of the staff of the entity will be assembled. Third the gap in the knowledge as to such government capability and the skills of its staff will be discussed. Fourth the path that research might take to fill that gap so that governments can achieve successful privatisation partnerships will be set.

2 Models of Partnership

This section of this paper explores the literature as to the modern models of government/non-government partnerships that have the capability of being used to provide ongoing services for government. There are two key models of partnership, the joint venture and the alliance with the key features that distinguish the partnership from other forms of privatisation being that the relationship between parties is horizontal (non-hierarchical) and all parties contribute resources and staff and are generally "involved in the action" [18]. This consideration of the models of partnerships that are suitable for the ongoing provision of services will not include the PPP principally because it is mainly used in the context of construction of infrastructure and the term is imprecise, sometimes being extended to encompass the alliance model.

Thus the concept of a partnership establishes the government and non-government parties with a theoretically equal legal status. This partnership can be formed by establishing a new entity (typically a corporations law company) to which each party contributes specified assets e.g. infrastructure or intellectual property and has a specified shareholding (ownership), all directed at a specified purpose which is much narrower than the overall activities of any party.

The following paragraphs will explore the features of the joint venture and alliance having particular regard to the role of the government entity and its staff.

2.1 Joint Venture

The joint venture is typically established by the forming of a corporations law company in which the government and a private sector company are each shareholders. Where infrastructure or assets are key to the activity it is common that the assets are sold into the new entity [13]. The extent of shareholding by government depends upon whether the government wishes to get the project off the balance sheet or wishes to retain control. A joint venture may contract with another entity, possibly the same entity which is a partner, for the delivery of the core services.

An example is an Australian urban water system where the government has sold the water and electricity activities into tandem joint venture utilities partnerships. The joint venture is comprised of two equal partnerships each between the government entity and one of two large utilities companies. One joint venture distributes utilities services and the other retails those services. The two joint ventures are partnerships governed by a single governance board applying formal agreements established between the three parties. The government entity has entered into a 20 year contract with the two partnerships for the operation and maintenance of the water system which remains owned by the government.

The staff (approximately 1,300) were seconded to be employees of the two joint ventures by way of legislation passed by the relevant parliament. Only 30 staff (approximately) remain in the government entity. They provide policy advice to government across all utility services, manage the contract for the water services and support the board of the government entity. The joint ventures are governed by a single board comprised of equal numbers of nominees from the private companies (three members) and the government company (three members drawn from the board and executive of the government entity). Thus the seconded staff are subject to the direction of this board and have been required to achieve increasing, competitive levels of productivity as measured and published in the annual *National Report: Urban water utilities* [10].

The configuration of the joint ventures and performance of the staff were found to have a direct causal link to achievement of the closely specified objectives of the government. The objectives were specified in performance measures which ranged from financial through to customer satisfaction. The performance targets were adjusted 4 or 5 yearly by negotiation with the government entity, this period aligning with the re-set of prices by the independent regulator. The joint venture advised that the inability to adjust the targets more frequently made its role difficult because of frequent increase in costs, e.g. energy, chemicals and labor.

The capability of the government entity was completely redesigned at the time of establishing the joint ventures. At the time of the research the joint ventures had been in operation for approximately 10 years and the government entity was governing the contract arrangements with the joint ventures to the satisfaction of all independent review bodies e.g. health authority, environmental authority, auditor-general, independent regulator.

The matter of the staff contribution to the achievement of the government's objectives of privatising must distinguish between the two different groupings of staff, the small staff of the new government entity and the staff employed by the joint ventures which was formed around a core of staff seconded from the government entity some 10 years earlier.

The question of the suitability of the staff of the government entity was not explored deeply as the focus of the research was upon the performance of the steward entity, the joint ventures, and unlike other case studies in the research, there was no suggestion of the government's objectives not being achieved.

The joint venture staff were found to have contributed significantly to the successful achievement of the government's objectives by way of their knowledge of the water system and customer needs, their dedication to providing water services, and the close match between the area served by their organisation and the geographical bounds of the regional community in which they lived.

The joint ventures were found to achieve the objectives of the privatisation by way of the tight governance and control exercised by the government entity and because of the sense of responsibility to the joint ventures and to the community on the part of the joint venture staff.

2.2 Alliance

Whilst the alliance form was initially used as a form of partnership between government and specialist contractors for the construction of infrastructure [16] it is increasingly used to carry out operations and maintenance work, customer service or capital works in Australian water systems. Alliances are distinguished from joint ventures and other partnerships in that an alliance is built on an explicit 'no-disputes', 'no-liability' framework and has a much stronger emphasis on teaming than these other relationships [3]. Also alliances are characterised by innovative features which address the key issues of risk apportionment, flexibility to focus on unspecified or evolving government objectives and gain/share pain/share arrangements. The alliance form of contract was developed as a response to the experience of traditional contracts which were typically incomplete in their specification of outcomes required in the comparatively distant future encompassed in their long contract period [3, 12, 16], found that typically alliance contracts:

1. share risk equally between customer and supplier;
2. include a 'no-disputes clause' which prohibits recourse to external disputes resolution (including litigation);
3. preclude liability between alliance participants for loss, damage or negligence; and
4. provide that all transactions are of an 'open book format', and all cost escalations or savings are shared between the parties.

In the public sector context "…the project team is integrated; it is required to act in good faith, with integrity…and make unanimous decisions and recommendations on all key project issues" 4. The alliance contract is typically structured to incentivise the parties to work quickly and collaboratively to resolve issues as they arise and work cooperatively to complete the project on time and within budget, requiring the government entity and its staff to instigate and foster relationships with non-government partners.

The water system stewardship research involved two case studies which demonstrated the operation of the alliance model. Case study one was a 10 year contract between a government water entity and a consortium of a private civil construction company and an engineering services company for operations and maintenance and capital works plus works for third parties in the name of the government entity.

The relationship was configured in a typical modern alliance form e.g. risk was allocated to the participant best able to bear the risk, the government entity contributed a significant number of employees, there was a *no-blame* clause in the contract and all transactions were transparent and costs and gains were shared between the parties. The Alliance was found to be a "virtual" organization with each participant retaining their own assets, entering into contracts in their own names and the staff being employed by whichever of the participants was appropriate. A formal agreement commits all parties to ensuring the highest standards of probity, full transparency and open discussion of all financial and operational matters and documents, including open-book accounting. The agreement requires that all decisions of the board be unanimous and *best for alliance.* The Alliance was characterized by all informants asserting that annual adjustment of the targets for performance measures and the incentive payment being tied to the achievement of these targets led to a highly focused sense of responsibility. The government entity was found to be highly capable in its dual roles of contract management (with the alliance) and in participating in the alliance. The alliance satisfied the demanding government objectives for this privatisation, without the government surrendering ownership of the system.

The government entity contributed approximately 450 staff of the overall 1,300 staff of the alliance reasoning that it wished to maintain the capability to operate and maintain the water system and to maximize the career opportunities of its staff. There was strong evidence of collaboration between the three partner organizations and between their staff. A new brand name was created and all staff were relocated to a new site. A high level of reciprocated trust was evident with informants attributing this to there being contractual experience between the three parties which preceded the alliance and to the experience of the private participants with alliance relationships throughout the world.

In contrast, case study two was two identical contracts between a government water entity and two unrelated private companies for the provision of water system operations and maintenance in contiguous regions. The contracts were labelled "alliances" by the government but whilst having some features of an alliance e.g. transparency of transactions, gains and pain were not shared and the government entity did not contribute a significant number of staff. The underlying contractual relationship was that of a traditional contract. The government went to market for a single alliance saying that it was experiencing diminishing returns from its reform efforts. Tender documents showed the government believed that the existing "alliance" arrangements had not always encouraged strong co-operative focus on business improvement and that there was a lack of alignment of goals and objectives and of collective responsibility for outcomes. The government saw the modern alliance form of partnership as resolving these issues.

The performance of government entity staff was identified by private participant informants as impacting negatively on the ability of the private participants to act in the interests of the government entity. Private company informants put the proposition that the government entity had an immaturity as to understanding the legitimacy of the contracted-out business model and a deficiency in capability to manage the contracts. The government entity management and staff were said to focus on short-term cost, adopt a command-and-control approach and not understand the operational detail of their business.

The replacement NG alliance addressed many of these issues by reforming the performance measurement and incentive arrangements and adding a substantial number of government entity staff to the alliance. This mixing of staff into the alliance was achieved by broadening the scope of the alliance to include planning and capital project functional sections which had been involved in an adversarial relationship in the previous model.

Bringing together the evidence from both cases, the following factors which contributed to the alliance model achieving the objectives of the government:

- Risk being allocated to the participant best able to bear that risk
- Contractual outcomes specified with great clarity
- Transparency of transactions between alliance participants
- Information symmetry
- Capacity to frequently (annually) adjust performance targets
- Intense measurement, rigid reporting and incentives to private parties
- Transparency to the public through external reporting and scrutiny
- Long term of contracts
- Each party contributing a significant proportion of the alliance staffing
- Capability of government entity to manage contracts with private sector
- Reciprocal trust

2.3 Discussion

This consideration of the two major forms of privatization partnership, the joint venture and the alliance, has focused on the closely related matters of government entity capability and the staffing arrangements. This preliminary scan of the literature has shown that governments choose to privatize, and choose a partnership model because of a shortfall in capability on the part of the government entity as judged against expectations of continually improved service delivery. The shortfall may be at an organization-wide level e.g. customer service orientation or commercial acumen. The shortfall may be in person-specific skills e.g. project management skills or specialist welding skills.

Governments utilize the partnership model to obtain these benefits of the non-government sectors whilst achieving a public sector benefit namely the retention of ownership of the core asset or government maintaining the capability to operate a key community asset.

However the very decision to make a government entity a member of a privatization partnership places the entity and its staff in an environment which will require the organisation to evidence different, typically commercial capabilities whilst invariably operating in a public service legal and cultural environment.

The nature of the capabilities required will be explored in the following section with the objective of developing a template for future, more detailed research.

3 Capabilities and Skills Required

The preceding section described the general features of the government/non-government joint venture and alliance models and utilized three privatization case studies to provide information as to the experience of the operation of those models of partnership. The availability of such empirical data as to the operation of the joint venture and alliance models in the operations and maintenance or ongoing service context is limited. Yet these case studies have shown the partnership form of privatization to require the government entity and its employees to succeed within an environment characterized by the range of private sector commercial pressures—all whilst remaining subject to public sector accountabilities. For the purpose of understanding how the government entity might successfully meet that challenge the knowledge available as to the capabilities required of the government entity and the skills required of the staff of the entity will be explored in the following paragraphs.

Prominent within the underdeveloped area of literature specific to the capability of the government entity and its staff is the work of Alford [1] who identified inter-organizational trust as crucial to the success of the partnership and identified obstacles to the maintenance of inter-organisational trust. The following paragraphs will set out the issues and actions to mitigate those obstacles as identified by Alford [1] with a view to developing a listing of the areas governments seeking successful performance by the government entity must address.

3.1 Organisational Issues and Actions

Reference [1] believes that trust between the participants is essential for any partnership but that the performance of the public servant may be rendered problematic by the following four structural and operational imperatives specific to the workings of government:

- turbulence—turnover of leadership, reassignment of staff, restructuring, funding and political re-prioritisation;
- the intra-governmental complexity caused by interdependency of government agencies (multi-function agencies or multiple agencies);
- accountability requirements of the public sector;
- organisation cultures of the government and non-government partners will differ resulting in a dysfunctional relationship.

Turbulence is harmful turnover of leadership by organisational restructuring, reassignment of staff, funding changes and political re-prioritisation which is more frequent than in private firms. Turbulence results in continual resetting of the rules which damages the ability of the government entity and its staff to maintain the support and trust of the non-governmental organisation.

Intra-governmental complexity is caused by interdependency of a number of government agencies (within or beyond the government entity) to produce public value e.g. law and order, and their competing priorities. This clash may subject the partnerships to demands at odds with their purposes causing the non-government partner to turn to the government entity to redress the conflict.

Accountability requirements: Financial reporting obligations, public service employment protocols, freedom of information laws, expenditure delegations, and government purchasing rules and procedures which ossify into rigid and elaborate systems of a generic nature, not tailored to the circumstances of the partnership. Alford [1] observes that these accountability mechanisms constrain the scope of the government entity staff to adjust when unexpected circumstances arise in partnerships.

Organisational cultures of partners differ, and the perspective that organisational culture is what people in an organisation believe about how things work in organisations and the behavioural outcomes of those beliefs. Where two partner organisations have differing cultures, core values and beliefs then it will be difficult to engender trust and commitment to the partnership purposes.

3.2 Other Issues and Factors

In listing these issues obstructing trust, Ref. [1] had judged that trust was highly important to the resolution of other factors which themselves are obstacles to the government entity being successful in the partnership. The threshold point that the work task faced by partnerships is often the more difficult of those faced in public administration. Further the research found if trust was achieved was key to the success of the joint venture and alliance models in the water case studies.

The difficult nature of activities allocated to partnerships was identified by [1] who observed that partnership is the form most suited to complex and evolving bundles of services. The partnership is chosen because the task is problematic and the roles of contributors to the particular service or outcome were difficult to distinguish. Put another way, as the partnership is often applied to difficult (if not wicked) service delivery problems the government entity and its staff are consistently faced with a more difficult challenge than that found in the classical buyer/provider relationship.

Information symmetry (no party being disadvantaged by another party having information denied to the first party) was seen by [1] as engendered by trust and in turn allowing the parties to adjust their processes, innovate and increase effectiveness. The water system joint venture and alliance revealed high levels of transparency of information within the partnerships to the point of transaction data being shared, amounting to information symmetry at all levels of the operation. This complete sharing of information was a key element of the cultures of each case study partnership and made possible the performance management and reward systems. Accordingly, rather than seeing trust as engendering information symmetry it is suggested that a minimum expectation of a partnership is shared, complete partnership information.

3.3 Discussion

This paper has followed the thread developed by [1] in exploring the obstacles to the government entity and its staff maintaining trust in the partnership. Broadening that thread, the factors which support the capability of the government entity and its staff to be effective in the water system case studies were explored and linked to the issues identified by [1]. There is considerable commonality suggesting that the way forward is to combine the issues or factors which must be addressed by governments seeking to ensure success of the government entity.

Accordingly this preliminary consideration of the partnership literature suggests that the following factors and features are highly important to the success of the government entity (and in turn its staff) in the partnership:

- Allocate a task or outcome to the partnership which is achievable
- Reconfigure the organizational structure of the government entity to better complement the partnership
- Mitigate intra-governmental complexity by active development of the wider authorizing environment
- Accountability regime tailored to the specific risks of the partnership
- Active crafting of a shared culture in the partnership
- Shared, complete partnership information
- Government entity staff in each role being chosen for their suitability to the new partnership role
- Government entity staff who interface with the non-government staff do so on a team basis to ameliorate the impact of reassignment of staff

4 The Knowledge Gap

These eight factors have been drawn from narrow research areas, the operation of trust in partnerships and the stewardship of critical infrastructures by various models of privatization. This listing of factors does not purport to portray the complete range of factors which must be addressed if a government entity is to be a successful member of a partnership. The potential for key factors to not be caught up in this preliminary process is large. A process based on obstacles and issues offers the real possibility of not identifying factors which contributed to the success of the government entity in an unremarkable manner. Similarly research involving a limited number of case studies from within one of the infrastructure sectors may not provide knowledge that is generalizable to the broad range of modern privatization partnership activities. Thus the research relied upon in this paper does no more than illustrate the possible benefits of future research.

However this data does illustrate that privatizations if not configured in ways which recognize the limitations of the government entity (the “alliances” which did not have the required allocation of risk, incentives or mixing of staff) will not achieve the objective of privatization. The joint venture and alliance which were configured in accordance with the key features of the models [3] paid close attention to the design of the roles of the government entity and to crafting the relationship between staff of partnership members and achieved the objective of the privatization. In that way the water case studies provide an example of the direction of future empirical studies.

The scope of the contestability and privatisation literature [6, 9, 11, 14] brought focus to the range of typical forms of privatisation and in so doing presented a considerable body of knowledge as to the skills, knowledge and experience which the non-government organisation can bring to a partnership. However there is not a comparable body of knowledge regarding the government entity and its staff.

Such focused knowledge is highly important to the success of privatization partnerships, not only because partnerships are often allocated difficult activities [1] and are subjected to heightening expectations as to service delivery, but also because the community is not tolerant of failures in privatizations.

5 The Research Path

As the wave of privatisation of government services reaches those not previously judged suitable for privatisation the partnership family of models is increasingly being employed by governments desperately focused on their ongoing financial viability and subjected to expectations by the community that service delivery will continually improve. Partnerships may be allocated the more difficult privatisation roles resulting in the dual roles of role of the government entity and its staff of managing the contract and being a member of the partnership delivering the service being very difficult. Thus it is imperative to the success of privatisations that governments and key decision-makers such as the CEO of the government entity fully understand the factors which positively and negatively impact the government entity.

The privatisation literature, specifically that going to the operation and performance of the partnership models e.g. joint ventures and alliances does not fully develop the factors which impact the success of the government entity and its staff as a member of the partnership. Accordingly the objective of this research is to develop a comprehensive listing and explanation of the factors which impact the effectiveness of the government entity in contributing to the partnership.

Faced with the government entity element of the literature being underdeveloped, or at best dissipated in many sources, the path of this proposed research will proceed in stages, each informing decisions as to the conduct of the next stage.

The first stage will interrogate the broad privatisation literature with the objective of gleaning direct or indirect data regarding expectations or actual performance of the government entity in partnerships. It is proposed to tease out the nuances of the variances within the partnership model e.g. the differing configurations of alliances, and the impact of those variances on the role of the government entity. The framework of factors developed in this paper based on the work of [1] will be modified based on information gathered in this stage.

The second stage assumes that the first stage will not deliver complete information and explores the literature of other disciplines and sectors to find information regarding the expectations upon government entities in partnerships. Examples are procurement and law literature and housing, health or social services literature. The framework of factors would be finalised in this stage.

The third stage will be utilised to analyse the data and determine how the findings can be best presented to satisfy the needs of academics, government and practitioners such as government CEO's. The framework and findings will be tested with typical users.

This staged research is being carried out to develop knowledge to assist decision-makers and their advisors to understand the issues which must be addressed in the operation of a partnership and before government enters into a privatisation partnership. This paper sets the path for research which will satisfy underdeveloped aspects of the privatisation partnership literature and contribute to government entities and their staff being more effective in their role of service delivery.

Acknowledgment This project is supported by the Cooperative Research Centre for Integrated Engineering Asset Management (CIEAM).

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Implications of Cadastral Systems on Engineering Asset Management

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Abstract Fixed or immovable assets include engineered infrastructure such as buildings, bridges, electrical and water utilities, roads, railways, and manufacturing and processing plants. These assets are built on land that often have inalienable rights implications, and in most jurisdictions, proposals to acquire and/or establish fixed or immovable assets, or even to deploy and utilize certain classes of movable assets must comply with a multitude of legislative stipulations. For example, the development of land through the establishment of an immovable asset may be embroiled in legal disputes between contending stakeholders asserting inalienable and alienable rights to land titles. Such disputes add to the costs of capital development projects, as well as the cost of utilizing major assets, and influence decisions as to where an asset intensive business venture may be located. Legislation not only provides the means to resolve ownership/custodianship rights but also, it stipulates legal imperatives for control and utilization of engineering assets. It is in this regard that this paper discusses some of the implications of land registration and cadastral systems on the management of major engineering assets.

Keywords Engineering asset management · Cadastral systems · Legal imperatives

1 Introduction

Major engineering assets such as airports, manufacturing and processing plants, water extraction and treatment plants and distribution systems, electricity generation plants, transmission and distribution systems, shopping malls, roads, railways

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_4

and other infrastructure are built on land. In most jurisdictions, land is treated as a natural asset, and in indigenous areas in particular, ownership/custodianship and exploitation of land are often vested in hereditary inalienable rights. By convention, the creation and establishment of an engineering asset on a piece of land is regarded as *developing* the land or making the land more valuable in economic and socio-political terms, sometimes neglecting the sustainability considerations.

In the first instance, access to land has to be obtained before it can be *developed*, and the process of obtaining access depends on the registration and cadastral system that confers title and establishes the rights to ownership, custodianship and exploitation of land. In the second instance, the zoning of land often requires granting of alienable right or permission to develop the land, for example, to establish fixed/immovable assets, and/or operate mobile/movable engineering assets. In the third instance, excise taxation rules may stipulate peculiar declarations on certain classes of movable assets before they can be deployed on landed property. This means that processes of land registration and certification have ramifications on the cumulative costs of developing and establishing, as well as operating, maintaining and decommissioning of an engineering asset such as a rail line, a dam, a mineral extraction, processing, and refining plant, or any type of building for that matter. Furthermore, excise taxation may also be applied to impose right of tenure costs for the deployment and usage of certain classes of movable assets like motor cars and mobile equipment. In simple terms, this also means that both immovable and movable engineering assets have to be legally *registered*, so that the registration process similarly confers certain rights to ownership, custodianship, control, deployment and utilisation of an engineering asset.

Most organisations require engineering assets that are built on, or erected on land in order to conduct business, and the processes involved in acquiring land for such assets are sometimes embroiled in legal disputes between contending stakeholders, especially where land registration and associated cadastral system are misaligned betwixt governance structures and exacerbated by the modern realities of globalisation and sustainability. The erection of a shopping mall, the construction of a road or railway line, the development of an airport infrastructure, the establishment a manufacturing or process plant, can easily be stifled, not only by environmental activism but also, by legal disputes as to ownership or custodianship of the land. Such disputes have taken on new significance in the modern era of globalisation and sustainability imperatives. Both practitioners and scholars would readily acknowledge that the acquisition of a major engineering asset saliently involves the location where the asset is to be deployed. Hence, the processes involved in acquiring engineering assets must comply with a number of legal regulations and legislative provisions. The prominence of environmental impact assessments is a case in point. There are many legislative directives in most jurisdictions (see, for example, Ref. [15], and a key feature of legislation stipulates that consultation with the stakeholders is a primary requirement for landed property development projects, even though the process of identifying stakeholders may not be trivial taking into consideration the mix and plurality of customary and state laws, and formal, informal, indigenous and traditional settlements.

This paper briefly discusses the land registration and differences between cadastral systems, in the context of the importance of landed property rights on investment and management of major engineering assets. Section 2 provides a brief background to land registration and landed property transfer processes. Section 3 highlights the role of cadastre systems with some contrasts, while Sect. 4 cites some examples of the implications of land registration, property transfer and cadastre systems on investment and management of major engineering assets.

2 Engineering Asset Management and Enterprise Risk Management

Organisational structures for land management differ widely between countries and regions and reflect cultural and judicial settings [14]. The purpose of any legal jurisdiction is to regulate the relations between its subjects (i.e., its peoples), in order to maintain order within the society concerned. These include relations between a government and its peoples. The allocation of property rights within many societies have been significantly derived from traditional rules of land tenure. The rules more or less define the processes that govern the granting of rights to access, use, control and transfer of land and landed properties, stipulating, in some cases, restraints and responsibilities. Investors recognize that, without secure land rights, that is, titled land ownership rights, there is increased risk to long-term sustainable development of engineering assets deployed on farmlands, coal mining and rock quarrying sites, or oil and gas exploration and drilling platforms [3] and [9]. Most formal rules of tenure tend to categorise land as follows:

i. private—incorporating the rights of an individual or groups of people;
ii. communal—rights assigned and conditioned on community rules
iii. open access—non-exclusive rights
iv. state property—rights assigned to public sector authority

In formal settings, land registration and cadastre systems capture and record information on land rights. With customary land tenure prevalent in some indigenous areas, information may be held within a community in tacit form through natural demarcations and collective memory of witnesses. Documents generated from such informal tacit information may be used by the community to recognise customary tenure rights. In formal settings, rights may be enforced through a system of courts and tribunals. Perplexingly, in many countries, formal and customary or indigenous land administration co-exist [18], even where official land registry systems of private ownership through legal documentation do not recognise customary land rights and other local agreements [27]. Some argue that the formalisation of land rights through titling may have little impact in countries or areas where existing rights are already secured through informal and customary administration. The success of a registration system is not dependent on its legal or technical sophistication, but on whether it protects land rights and whether it records such rights efficiently and at low cost [26]. Traditionally, most customary tenure favour men, granting women rights through existing marriage to a husband, or via the father, brother or son in the case of an unmarried woman [9].

Security of tenure is the certainty that someone's land rights will be recognised by others and protected if these rights are challenged [1]. Reference [25] contends that complex indigenous rights have gradually emerged to afford protection under international law, and posits that the sequence of precedence of customs and laws regarding land rights only complicate transactions and agreements for developmental projects. The importance of long term security has wide ranging ramifications, for example, people may be reluctant to effect improvements on property in the absence of secure land rights [11]. Reference [24] points out that, in some countries where vast areas of communal land are used solely for subsistence, the customary methods of management may seem adequate. Where commercial development of communal land has taken place, there may be the need to support existing customary methods of management with regulations, especially where present tenure security provided by traditional conventions may not sufficiently protect indigenes and locals against claims made by global multi- and trans-national corporations.

2.1 Indigenous Legal Land Transfer Systems

Most indigenous legal systems occurred as a result of age-old traditions and customs that over time became respected as 'law'. As the values of the community changed, so did the law. Customary law was originally not recorded in written statutes, textbooks and law reports. Traditional court procedures were conducted orally and the law was orally transferred from one generation to the other. This occurred mainly through the active participation of adult men. The community thus had broad knowledge of the general law. Disputes were decided in the community as it not only affected the individuals concerned but also the future relations between members of the community. Individual family members, or the family, and the community, were considered to be the role-players, and the interests of the community were accorded higher priority than those of the individual [10]. Despite many cultural, linguistic and other differences, indigenous people the world over affirm special relationships to their ancestral lands. Individuals and groups of people often derive much of their own identity from a deep sense of attachment to land that has been occupied by their ancestry over generations [2].

According to Ref. [7], in terms of indigenous law, general property belongs to the family as a whole, but, the head of a family has top priority control especially over the landed assets. In the principle known as *primogeniture*, the head is not the personal owner of landed property but, the family's rights are vested in the head of the family; the oldest child succeeds the family head, and takes full responsibility for the inalienable landed properties. An individual's share of rights to family property depends on status determined by factors such as sex, age, marital status, and matrilineal or patrilineal order. Irrespective of status, an individual may not act independently of the group, thus, indigenous customs generally operate on norms which the whole community regard as binding and which should be obeyed. This situation is rapidly changing in many communities that are also governed under formal rules of law. Reference [23] points out cases where dominant persons use access to formal law to exert excessive influence causing land to be alienated without the consent of the family, and such situations may be exacerbated when the land is transferred to investment and development stakeholders.

2.2 Modern Formalised Property Transfers

In more modern and formalised land administration situations such as provided in *private law western* legal systems, the rules of law are applied to decide the powers of the holder of a right, as well as the limits to the content of a right. A right held by a legal subject (whether individual or group) imposes a duty on other legal subjects to respect that right [11]. Real rights may be acquired in respect of ownership to freely use and enjoy, alienate or sometimes, to destroy a property [22]. In specialised legal systems the emphasis is placed on the individual, whereby an individual may uphold his or her rights even when this is against the interests of the community or the state. Formal land administration procedures can be time consuming, cumbersome and costly [6]. High transaction costs may result in land dealings taking place informally without proper recoding procedures.

As illustrated in Fig. 1, for property transfer to take place, a number of role players and numerous transactions and processes may be involved. For example, an offer-to-purchase a property may be concluded between a buyer and a seller, and in some jurisdictions, with professional assistance from a registered estate agent. The offer fulfils all the requirements for a valid contract to be concluded, that is, buyer, seller, and estate agent having the necessary capacity to act, the ability to perform in terms of the contract, in lawful compliance to formalities. The offer contains the identity of the parties, the *essentialia* of the contract, signatures of the parties, and other material terms in the form of provisions and conditions of the agreement. There are two *essentialia* of a contract of sale, namely delivery and payment of a price. A buyer may obtain a loan to afford the property price. The lender (typically a bank) may request due diligence valuation before granting the loan to bond or mortgage the property. A bond attorney may be instructed to carry out registration of property and recording of transfer of title at the deeds office where records of property titles are kept.

In essence and in most jurisdictions, formal property transfer involves *conveyancing* processes such as [5]:

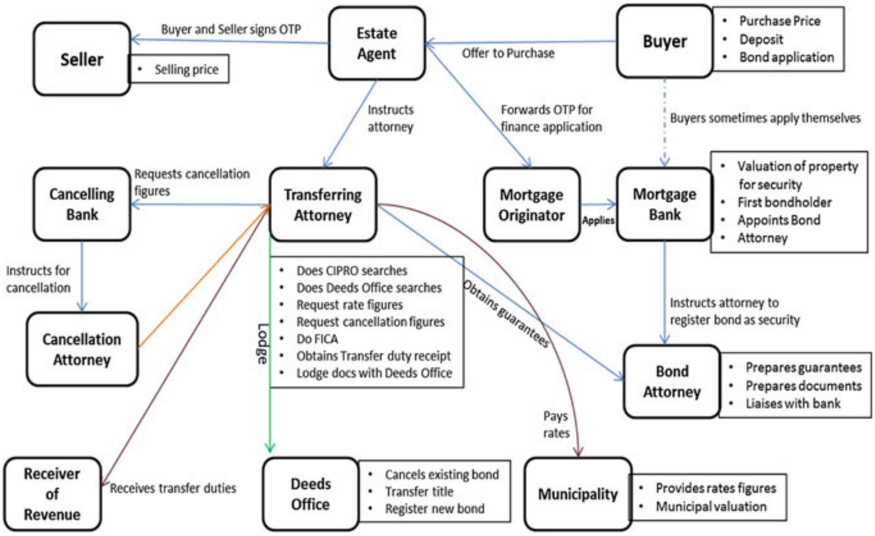

Fig. 1 An illustration of *conveyancing* processes for transfer of landed property [6]

i. valuation of property (e.g., by actuarial scientists, quantity surveyors, real estate agents)
ii. financing activities (e.g., by banks, financial institutions)
iii. contracts (e.g., by attorneys, notaries, and conveyancers)
iv. statutory registration (e.g., by local government, internal revenue), and,
v. custodians and owners (i.e., sellers and buyers).

Similarly, engineering asset management also involves:

i. valuation of an asset
ii. financing the acquisition, operations, maintenance and divestment of an asset
iii. contracts (e.g., supply chain, service delivery)
iv. registration of assets (for fiduciary and technical integrity compliance)
v. ownership and custodianship (legal responsibility).

The corollary is that landed property transfer involves asset management processes, hence land registration and cadastre systems form part of the broad information systems for the management of major engineering assets.

3 Significance of Cadastral Systems

The cadastral system is typically maintained by the state; it includes at least two databases [8] and contains public domain information to facilitate title searches and property transfers at commensurate transaction costs [1]. The basic component of any land administration system is the land parcel as identified in the cadastre [14]. In formal settings, the cadastre is established by state statute, typically:

i. as a register of owners where only the transaction is recorded [8], or
ii. as a register of titles [14].

The purpose of the cadastre is to protect the interests of owners and encumbrances by notifying all creditors, subsequent purchasers, and other interested stakeholders like investors and developers. The title is usually mandatory for commercial loans to be granted for the development of the corresponding parcel of land, thus a benefit of registered titles or deeds is that it provides access to credit which in turn may stimulate economic growth [7]. The absence of a cadastral system may result in lengthy and expensive chores to identify and trace land title to ensure that there are no encumbrances.

Interestingly, there are many countries with plural systems where both state and customary institutions continue to jointly manage and administer land issues. For example, in Ghana [1], private land refers to traditional land while state land refers to land acquired by the state from private land owners. Private land vests in communities that are represented by families and chiefs. In the traditional land market oral land grants are made before witnesses. Proof of evidence is therefore not based in writing, but by physical possession and occupation and the recognition by the members of society. In some parts of Ghana traditional land law has evolved to reflect a form of documentation for property transfers. With global stakeholder interests, it may be necessary to harmonize the plural systems to address socio-political challenges. In Rwanda and most countries in the South Pacific region, customary land constitutes 80–90 % of the total area, and the transfer of customary land is prohibited, except in accordance with custom [23].

Whereas far-reaching legal and institutional changes were initiated to provide secure land tenure and eliminate bias against female land ownership in Rwanda [4], however, most South Pacific governments have preferred to not intervene in land issues and allow customary processes and the principles of common law to regulate decisions and action taken in relation to customary land. One exception is Fiji, where complete control of the management of customary land is vested in a statutory body [23]. Several countries in sub-Saharan Africa have revised their land laws to grant legal recognition to customary forms of land tenure. Most of these reforms have taken place within the last 15 years. In Botswana for instance, customary land rights are secured by a customary land grant certificate which grants exclusive and heritable use rights to individual applicants. Botswana's land reform is seen as very visionary but exclusive and may be unsustainable in the long term [18].

Although many other countries in Africa exhibit slight variations of the Botswana and Rwanda examples, however, many development projects on so called indigenous lands have been negatively affected by transactions between governments and investment stakeholders [19]. The corresponding disruptions, delays and exorbitant costs, especially in legal fees, have resulted in many abandoned and mothballed development of major engineering assets. A few such examples are briefly described.

4 Examples of Cadastral Systems Implications

In Matladi v Greater Tubatse Local Municipality in South Africa, a claim to farm land which was in the process of being developed as a new township that includes necessary roads, water and electricity infrastructure, was challenged. Although the appeal was not upheld, there was much time and resources employed in the many court cases that lasted a number of years [26].

A civil action claim commenced more than 20 years ago regarding provincial forestry licenses that were granted in land occupied by six Indian Act bands. The Supreme Court of Canada delivered unanimous decision in Tsilhqot'in Nation v British Columbia on 26 June 2014. This decision will create challenges for governments and proponents who seek to initiate development projects on Aboriginal land in large parts of British Columbia, Atlantic Canada, northern Ontario and Quebec. All future activity on titled land will require the consent of the new title owners and may no longer be imposed unilaterally [17]. This decision will also impact on another development where the Enbridge's Northern Gateway pipeline project to the Pacific coast to export tar sands oil was approved on 16 June 2014. Chinese state-owned companies have invested more than $40 billion in Canadian energy in the past few years. Native groups are unanimously opposing the pipeline and tar sands projects [29].

In Vancouver a dispute over native land of the Peel River watershed started more than 10 years ago. The area has been marked for development and agreement has still not been reached. However, in Kitimat, a town in northern British Columbia, agreement was reached on 1 July 2014 for proposed liquefied gas projects to continue.

In 2012, an Indonesian court ruling affirmed the constitutional rights of indigenous people over land, following imprisonment and fined after ancestral lands were nationalised under government laws aimed at preventing illegal logging [21].

The increased demand for palm oil worldwide has created serious land conflict in Indonesia as land is being cleared without the consent of indigenous land owners [20]. Similar problems are being experienced in Liberia, Cameroon, Ivory Coast and the Democratic Republic of Congo with massive expansion of palm oil extraction and processing ventures. Governments are handing out permits without first consulting with the local communities. Outside companies are coming into take over forests and land of these indigenous people and local communities and this is creating much conflict [20].

5 Concluding Remarks

On the one hand, the IWR White Paper cited as Ref. [16] states that "…the economic assumptions surrounding the Panama Canal's expansion remain inconsistent …; predicting the expansions impact as well as the timing and location of the impacts on fleets (shipping vessels) and cargo is very challenging…". Remarkably, the six recommendations stated in the report make no reference to land rights, presumably because the titles have long been resolved in the well-established cadastral systems prevailing in the region. On the other hand, Ref. [13] discusses in reasonable detail, the issues of "land titling and economic restructuring in Afghanistan", while Domeher and Abdulai [12] argues that the "relationship between landed property registration and agricultural investment in the developing world are made defective in Africa by factors such as poverty, lack of appropriate agro-based infrastructure, and the fact that land registration per se does not improve the profitability of agriculture, neither does it improve access to credit".

Many examples of the implications of land registration and cadastral systems on engineering assets appear as stories in local print and electronic media in just about every jurisdiction in the world. The stories range from agitations to disputes between contending stakeholders regarding the scope, exclusions and limitations implied in either inalienable or alienable land rights and title deeds. It is not uncommon to read a newspaper story containing statements like (cf: [28])

> …the proof of concept version of the asset was erected without proper consultation and before a formal public participation process or advertisements. This does not represent a due or legal process…. The public comments will be submitted and the objections will be heard. Should the town planning tribunal approve the re-zoning application, XYZ will submit formal plans to erect the permanent structure…

In this case, a particular stakeholder group is protesting the installation of an engineering asset, for example, a mobile telephone tower in a residential area, even though the asset is being deployed to improve the mobile telephony coverage within the estate. Often, it is only when the frequency and the manner of reporting of such news item increases to a frenzy that the affected asset manager (owner, custodian, steward, operator, or maintainer) realizes that it is not just about engineering or technology but also about legal responsibility and corporate citizenship.

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A Decision Support Framework for Prioritization of Engineering Asset Management Activities Under Uncertainty

Michael E. Cholette, Lin Ma, Lawrence Buckingham, Lutfiye Allahmanli, Andrew Bannister and Gang Xie

Abstract Engineers and asset managers must often make decisions on how to best allocate limited resources amongst different interrelated activities, including repair, renewal, inspection, and procurement of new assets. The presence of project interdependencies and the lack of sufficient information on the true value of an activity often produce complex problems and leave the decision maker guessing about the quality and robustness of their decision. In this paper, a decision support framework for uncertain interrelated activities is presented. The framework employs a methodology for multi-criteria ranking in the presence of uncertainty, detailing the effect that uncertain valuations may have on the priority of a particular activity. The framework employs employing semi-quantitative risk measures that can be tailored to an organisation and enable a transparent and simple-to-use uncertainty specification by the decision maker. The framework is then demonstrated on a real world project set from a major Australian utility provider.

Keywords Project prioritisation · Decision support · Uncertainty

1 Introduction

Engineering asset managers must often make decisions regarding maintenance, replacement and capacity building activities in an environment of limited resources. Prioritisation of these activities is thus a key question. However, objectives are often varied, conflicting and interrelated, making optimal activity selection overwhelming without appropriate tools.

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_5

In large organisations, the selection of activities is complicated by a number of factors, e.g.

- The disparate nature of the activities and their values. Potential activities often have risks and rewards of a very different nature. For example, equipment breakdown can carry safety and financial risks while the procurement of a new piece of equipment may allow expansion of the business, carrying financial reward.
- The unavailability of an appropriate cost model. It is often difficult to assign dollar values to certain "intangibles" such as "reputation" and "safety." Nevertheless, such intangibles are important considerations for real organisations.
- The uncertainty of values. Uncertainty enters the analysis through inherent randomness as well as incomplete information, either as a result of the cost model or the decision maker making the evaluation.

The most relevant frameworks and methods for activity selection can be found in literature under the umbrella of the "capital budgeting" problem [1–5, 6, 7], which includes specific applications to R&D projects [8], healthcare [7], military base closure [9], and nuclear power plant project selection [10]. Generally, the capital budgeting problem is viewed from a mathematical programing perspective where the goal is to maximise the net present value (NPV) of the project collection, while more recent methods address uncertainty [8, 10–12].

Practitioners often base capital budgeting on priority lists [10], in contrast to mathematical programming methods prevalent in literature. While generally suboptimal, these lists can serve as the basis for transparent heuristics for activity selection [5]. This transparency is often favoured in practice, since mathematical optimisation techniques have opaque solution procedures and the sensitivity to uncertainty requires sophisticated analysis [10–12]. Such opaqueness makes intuitive and qualitative reasoning all but impossible. Another drawback is the tendency to employ NPV maximisation as the objective. Quantifying an activity's benefit in dollar terms is often not feasible, partly due to the difficulty in assigning costs to considerations such as "safety" and "reputation." In such situations, it is common to use semi-quantitative risk measures, which have considerable precedent in engineering analysis (e.g. Failure Mode, Effects and Criticality Analysis) [13, 14].

In this paper we develop a methodology for ranking asset management activities based on well-known semi-quantitative risk assessment techniques. We develop a model for project interdependencies and ask expert decision maker(s) to assess the consequence of deferring a project. As with any expert-based method, uncertainty in the judgement will be present. Our method directly addresses this uncertainty through expert assessment and describes how the uncertainty affects the prioritisation ranking.

The remainder of this paper is structured as follows. Section 2 details the ranking framework, including project deferral risk evaluation, multi-criteria fusion, modelling of risk aversion, and project interdependencies. Section 3 details a simulation algorithm for estimating the ranking distribution to assess the impact of the decision makers' uncertainty. Finally, Sect. 4 details a proposed decision support workflow and a case study based on activities from a real utility provider.

2 Ranking Framework

We consider the following scenario. The decision maker has a collection of potential activities to undertake. These activities may be repair, overhaul, renewal, procurement, augmentation or other activities that are designed to improve asset performance or capability. Due to resource limitations and other constraints, it is impossible to carry out all activities so the decision maker is forced to select a subset of projects that will go ahead. Alternatively, it will be beneficial for the following formulation to think of the decision maker as deciding to *defer* some of the potential activities. It is therefore desirable that the decision maker has a ranking of the most important projects, i.e. those whose deferral lead to the highest lost value.

This value is assessed by considering the risk that the organisation is undertaking by deferring the project. This risk could be financial, but it could also be risk due to safety, legislative obligation or reputation. An example of the latter is when deferral of a project would result in a breached agreement, damaging the reputation of the organisation in the eyes of the client/supplier.

In our discussions with practitioners, we found that they responded quite negatively to framing consequences in money-only terms. Decision makers made the case that they either simply did not have the information to make a sufficiently accurate cost model or did not believe that any cost model could adequately account for intangibles such as "reputation." For this reason, we adopt a semi-quantitative approach for consequence assessment. Such semi-quantitative analysis has ample precedent in national/international standards (e.g. FMEA/FMECA standards [13, 14]) and in intra-organisation standards, thus making it likely that practitioners will be comfortable making such assessments and enhancing transparency of the project consequence accounting.

In such a setting, an expert enters the probabilities for a given project into a worksheet in the format of Table 1. The rows of the matrix represent different consequences for the deferral of a project and the columns are the consequence numbers. The exact details of the worksheet will depend on the organisation's risk assessment standard. Included in such a standard would be guidelines for assigning a consequence number to an outcome. An example of this in the "Financial" category would be cost ranges for each consequence level.

Table 1 Deferral consequence matrix for project *i*

Criteria/ Consequence	0	1	2	3	4	5
	No Impact	Minor	Significant	Moderate	Major	Catastrophic
Criterion 1	$p_{i1}(0)$	$p_{i1}(1)$	$p_{i1}(2)$	$p_{i1}(3)$	$p_{i1}(4)$	$p_{i1}(5)$
Criterion 2	$p_{i2}(0)$	$p_{i2}(1)$	$p_{i2}(2)$	$p_{i2}(3)$	$p_{i2}(4)$	$p_{i2}(5)$
⋮						
Criterion M	$p_{iM}(0)$	$p_{iM}(1)$	$p_{iM}(2)$	$p_{iM}(3)$	$p_{iM}(4)$	$p_{iM}(5)$

The expert is responsible for filling in the probabilities of each consequence for each of the $\boldsymbol{M}$ criteria

In each cell, the expert enters the estimated probability that a consequence for is realised *if the project is deferred*. It should also be noted that a combination of expert knowledge and data can be utilised. For instance, if one of the criteria was "Financial" historical financial losses could be used to quantify the necessary probabilities, with the organisational standard denoting what levels of financial impact are considered minor, moderate, etc. Assessment of consequences for subjective or qualitative criteria such as "reputation" requires the professional opinion of one or more domain experts and managers.

The framework places no restriction on the number of criteria. However, they should remain as independent as possible. For instance, if the set of consequences includes a Financial category and a Regulatory category, and the impact of a breach of regulation is purely financial (that is, a fine) then the Regulatory consequence should be removed and its impact counted as part of Financial. On the other hand, if the Regulatory consequence entails both financial and non-financial components, the financial component should be accounted for under Financial but the non-financial part should be retained as an independent Regulatory consequence. Another example might be a project whose deferral causes a safety hazard. Consequences arising from a safety hazard will typically include financial components such as medical expenses or compensation, but the impact of safety-related events often goes beyond simple financial outcomes. A careful decision must be made as to how the separate components should be distributed between Financial and Safety categories to ensure each component is correctly accounted for in the decision calculation.

2.1 Deferral Consequence Model

We consider the deferral of a project to carry certain consequences for a number of different criteria important to the organisation. Let N be the total number of potential activities that are to be judged using M criteria. Let $\hat{C}_{ij} \in \mathbb{N}, i = 1, 2, \ldots, N, j = 1, 2, \ldots, M$ be a discrete random variable representing the consequence for the deferral of project i for criterion j. Each $\hat{C}_{ij}$ has a probability mass function $p_{ij}(c) = P\left[\hat{C}_{ij} = c\right]$ which is simply a row of the consequence matrix in Table 1.

The M criteria are combined into a single *project-level* deferral consequence as

$$C_i = \sum_{j=1}^{M} w_j u_j\left(\hat{C}_{ij}\right) \tag{1}$$

where w_j denotes the weight of criterion j and $u_j(\cdot)$ is a non-decreasing function. This project-level criterion will serve as the basis for preference, with a lower C_i implying a lower consequence for project deferral.

Since the consequence numbers are standard for an organisation, it is expected that a "moderate" consequence is equally risky whether it be a safety or financial consequence, implying that $w_j = w_k, \forall j, k$. If this is not the case, a number of methodologies may be utilised to set the relative weights, such as the analytic hierarchy process [15].

Despite the standardisation of criteria, it is still preferable to have a tool for expressing risk aversion, which may be dictated by organisational policy. For example, a policy such as "safety first" may prompt risk aversion on the safety criterion. In order to allow the decision maker to explore how this affects the resulting ranking, we employ a utility-like function, $u_j(\cdot)$ in Eq. (1). The simplest case is risk neutrality, in which case we have

$$u_{j,rn}(c) = c$$

On the other hand, if the organisation is moderately risk averse in criterion j, we use

$$u_{j,ra}(c; a, b) = \begin{cases} c & c \leq a \\ b^{(c-a)} + a - 1 & c > a \end{cases}$$

where a represents the consequence value beyond which the organisation is risk averse and $b > 1$. Strong risk aversion is modelled similarly, but with a more dramatically increasing function

$$u_{j,sra}(c; a, b) = \begin{cases} c & c \leq a \\ b^{(c-a)} + a - 1 & c > a. \end{cases} \tag{2}$$

The activities will be ranked based on the project-level consequences in Eq. (1). It will be convenient to utilise the probability mass function (PMF) of C_i in our following methods. Given our assumption that we have not "double counted" consequences with criteria, we may assume that, given that project i is deferred, each of the C_{ij} are independent. This allows us to compute the PMF straightforwardly using discrete convolution

$$p_i(z) = P[C_i = z] = (p_{i1} * p_{i2} * \cdots * p_{iM})(z) \tag{3}$$

where $(f * g)(z)$ denotes the discrete convolution operation. If the individual criteria cannot be considered independent given deferral, a model for their dependency would be required to determine the joint PMF. Such a model is not considered in this paper.

2.2 A Model for Activity Dependencies

So far, activity deferral has been considered in isolation; that is, it does not affect the deferral consequences of other projects. In this paper we will develop a model for pre-requisite dependencies.

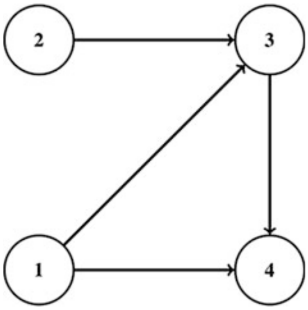

Fig. 1 A directed graph representing a pre-requisite relationship in a four activity collection

Activity j is said to be a pre-requisite of activity i if i can only be done if j is done. This implies that the deferral of j *induces* the deferral of i. To model these dependencies we borrow a few notions from Graph Theory [16]. Dependencies are represented as a directed graph where the directed connection indicates that a pre-requisite-type dependency exists between the nodes. An example of this can be seen in Fig. 1. In that example activity 1 is a pre-requisite of activities 3 and 4, 2 is a pre-requisite of 3, and 3 is a pre-requisite of 4.

An activity can have any number of pre-requisites or dependencies, though it is assumed that the dependencies are not circular, i.e. there is no directed path from any node that returns to the same node. This condition ensures that all dependencies are representable by a directed *acyclic* graph.

We are now in a position to define the *total deferral consequence* for activity i, which we define as

$$\overline{C}_i = C_i + \sum_{j \in D(i)} C_j \tag{4}$$

where $D(i)$ denotes the descendants of activity i in the dependency graph. Clearly, this total consequence takes into account the deferral consequence of each individual project as well as the induced deferrals.

3 A Method for Ranking Under Uncertainty

Using the consequence matrix and dependency model, activities can be ranked based on the total consequence of deferral, defined in Eq. (4). A straightforward method for ranking would using some measure of central tendency, such as the median or mean total consequence.

Yet, some important information would be lost. Namely, how certain are we that a project will be in position x Given the subjectivity and inherent uncertainty in consequence information, it would be helpful to the decision maker to have a notion for the range of possible activity rankings. Therefore, projects will be ranked on their median along with an assessment of the uncertainty in this ranking. In this section, the algorithm for determining this ranking will be detailed.

We begin by making some key definitions. We first sort the N activities by the total project consequences, $\overline{C}_i, i = 1, 2, \cdots, N$ in descending order

$$\overline{C}_{[1]} \geq \overline{C}_{[2]} \geq \cdots \geq \overline{C}_{[r]} \geq \cdots \geq \overline{C}_{[N]}$$

where $\overline{C}_{[r]}$ denotes the activity with the r th largest total deferral consequence. We define the *activity priority number (APN)* of activity j as

$$\begin{aligned} R_j &= \min r \\ \text{subject to:} \quad \overline{C}_j &\geq \overline{C}_{[r]} \end{aligned} \tag{5}$$

which is simply the number of activities that have a total deferral consequences greater than activity j. A bit of consideration should convince the reader that this definition assigns activities with equal total deferral consequences to the *lowest* rank.

Our ranking methodology will now center on finding the probability distribution of APN, i.e.

$$G_j(r) = P\left[R_j \leq r\right]. \tag{6}$$

Once we have this distribution we can compute any measure of uncertainty we wish. In this paper, we'll employ percentiles of the distribution, which can be computed as

$$r_{j,p} = \min_r \left\{ r \in \mathbb{N} | F_j(r) \geq p \right\} \tag{7}$$

where $p \in [0, 1]$ is an arbitrary percentage of the data. Using this definition, we compute the median as $r_{j,0.5}$, inter-quartile range of the priority number for activity j as $iqr_j = \left[r_{j,0.25}, r_{j,0.75}\right]$ and the 95 % confidence interval

$$CI = \left[r_{j,0.025}, r_{j,0.975}\right].$$

What remains is to compute the activity priority distribution number from Eq. (6). In this work, we take a simulation approach. First, the project-level consequences are randomly generated according to the distributions in Eq. (3). Then, the project dependency model is employed by using Eq. (4) to compute the total project consequences for each of the N projects. The projects are then sorted in descending order and the definition in Eq. (5) is used to determine the APN. The simulation process is repeated M times and the results are averaged to determine the priority number distribution of Eq. (6). The algorithm is summarised in Algorithm 1.

4 Decision Support Case Study on a Real Activity Set

We now demonstrate how the APNs can be utilised in a decision support framework. A real-world set of asset activities was collected from an Australian utility company (we cannot be more specific due to proprietary considerations). The potential activity set of 37 projects included augmentation, repair, replacement, and procurement activities. Their deferral consequences were assessed by experts within the organisation, who filled in the probabilities of each consequence number in a table similar to Table 1. This table included four sub-consequences (row of Table 1): Safety, Regulatory, Financial and Performance.

The expert entered the data into a custom Microsoft Excel spreadsheet, which served as a simple graphical interface with data quality checking. The sheet had a macro that exported the pertinent data to a Comma-Separated Value file and reset the sheet for the entry of a new project. The CSV files were imported into MATLAB and Algorithm 1 was employed to estimate the APNs. In MATLAB on a Windows 7 notebook with an Intel Core i5 processor, the simulation takes about 15 s to run with M = 40,000.

Algorithm 1 provides the probability distributions of the APNs, allowing the median, inter-quartile range, and 95 % confidence interval to be computed using Eq. (7). This allows the decision maker to assess the effect of the consequence uncertainty has on the ranking. The visualisation of the APNs with simple box plots is proposed as a way to visualise the results and assess the certainty of the ranking.

The results for the 37 activity set can be seen in Fig. 2, where they have been sorted according to their median APNs (denoted by solid dots). The project identifiers are on the vertical axis. There are a few interesting points to note that highlight the power of using APNs as a decision support tool:

- The three lowest APNs, which are highly certain given their small 95 % confidence interval. This indicates that these projects are high priority and should not be deferred;
- The next 5 activities have equivalent median APN and almost identical confidence intervals, making them effectively equivalent;
- Above Activity 29 there is a clear upward shift in the APNs and their confidence intervals. The decision maker may choose to defer these final 12 projects.

In the final case, the decision maker would remove the final 12 projects from consideration and *re-run* Algorithm 1. To see why this is needed, consider Fig. 2 again. The two large asterisks indicate activities that are dependencies of the first activity. When the final 12 activities are deferred by the decision maker, then Activity 04 has one less dependent project, and its deferral will *not* induce the deferral of Activity 03 (it has already been deferred). The new APN ranking after deferring the last 12 activities can be seen in Fig. 3. We see that Activity 04 has dropped in median APN to 2 and has only one dependency, denoted by the large asterisk.

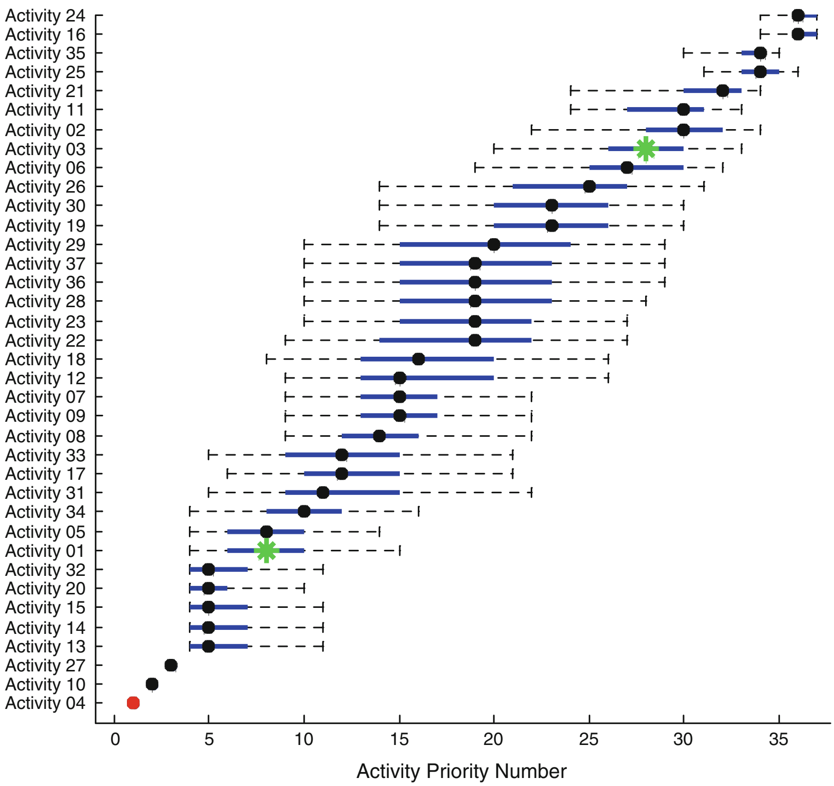

Fig. 2 Box plots for the activity priority number for the real-world project set. The higher APNs indicate higher priority

Finally, we explore what happens if the organisation was extremely risk averse in the safety criterion. To do this, we recompute the project consequences in Eq. (1) using the strong risk aversion function of Eq. (2), i.e. $u_j(\cdot) = u_{j,sra}(\cdot, a, b)$. We then employ $a = 2$ and $b = 2$ which models a strongly increasing slope after a consequence number of $\hat{C}_{ij} = 2$. Clearly, depending on the organisation, these parameters may be different to express different levels of aversion. We then re-compute the project-level consequences using Eq. (3) and re-simulate.

The results can be seen in Fig. 4, where the order of Fig. 1 has been used for easier comparison. We can see that the strong safety aversion has affected only two rankings significantly: Activity 20, which is fairly clearly the fourth-highest-ranked project and Activity 29, whose median ranking has decreased by 2.

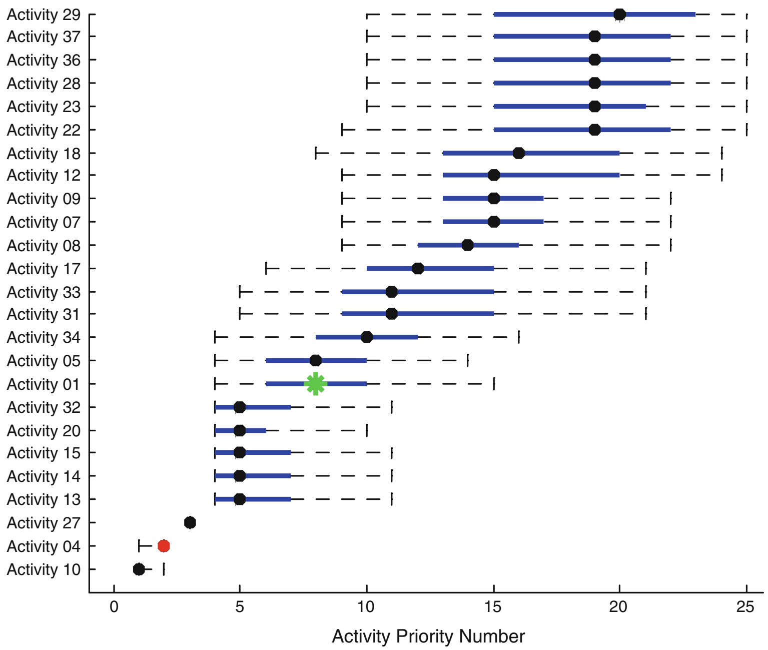

Fig. 3 APN after deferral of the 12 lowest-ranked projects. Note that the deferral of a dependency has lowered the APN of Activity 04

Algorithm 1 Estimation of activity priority number distribution.

Input: M, $p_j(z)$, $j = 1, 2, \ldots, N$
Output: $\hat{G}_j(r)$, $j = 1, 2, \ldots, N$
Initialize:
  Sort projects topologically
  $\hat{R}_j(r) = 0, \; \forall j, r$
for $m = 1, 2, \ldots, M$ **do**
  for $j = 1, 2, \ldots, N$ **do**
    Generate C_j according to distribution in Eq. (3)
    Compute $\bar{C}_j$ using Eq. (4)
  end for
  Sort $\bar{C}_j$ in descending order $\rightarrow \bar{C}_{[r]}$
  for $r = 1, 2, \ldots, N$ **do**
    for $j = 1, 2, \ldots, M$ **do**
      if $\bar{C}_j \geq \bar{C}_{[r]}$ **then**
        $\hat{R}_j(r) = \hat{R}_j(r) + 1$
      end if
    end for
  end for
end for
for $j = 1, 2, \ldots, N$ **do**
  $\hat{G}_j(r) = \frac{\hat{R}_j(r)}{M}$
end for

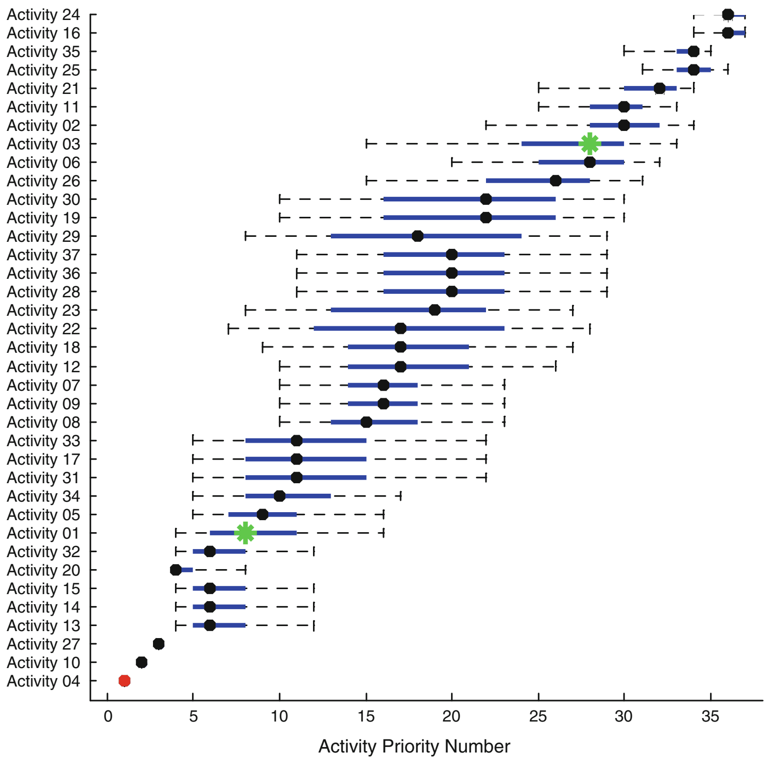

Fig. 4 APN under strong risk aversion in the safety consequence. Note that the projects are displayed in the same order as Fig. 2

5 Conclusion

This paper has presented a framework for ranking engineering activities under uncertainty. The framework employs common semi-quantitative techniques to assess the consequences of deferring an activity. Experts are used to assess the probability of each consequence number occurring along different criteria that are important to the organisation.

A ranking methodology was employed that enabled multi-criteria ranking in the presence of uncertainty, and described the effects that uncertain valuations may have on the priority of a particular activity. Finally, the framework was demonstrated on a real world project set from a major Australian utility provider.

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Planning Rehabilitation Strategy of Sewer Asset Using Fast Messy Genetic Algorithm

Jaena Ryu and Kyoo-hong Park

Abstract The present study suggests a model for planning sewer asset rehabilitation strategy, developed with an optimization algorithm. The fast messy genetic algorithm was used to suggest an optimized rehabilitation strategy with an objective function to minimize total costs of sewer rehabilitation and I/I treatment. The developed model was tested in a selected case study network of Banpo in Seoul, South Korea. Within a reasonable and finite number of searching, it was successful to obtain optimum rehabilitation schedules and costs for both cases of optimization problems that were for individual sewer lines and for group of sewer lines. It is expected that this model can contribute as a decision making tool in prioritising of sewer rehabilitation projects and estimating the optimal budget for officials of municipalities or local government. Also, this model can act as a supplemental tool in conducting the cost-effective analysis for sewer rehabilitation projects for engineering consultants.

1 Introduction

Sewer systems are valuable public assets in many metropolitan cities. While structural quality and functional efficiency are fundamental to guarantee those performances, they face different problems because of those characteristics embedded underground. The American Society for Civil Engineering (ASCE) [1] reported that most sewer lines in the US reached state of near collapse in 2005. Undetected defects would get more severe. In England and Wales, about 4,600 sewers were collapsed each year, and this means approximately 20 collapses per

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_6

100,000 properties [2]. Reference [3] reported that 20 % length of total 304,000 km were considered as critical sewers and about 225 km of critical sewers were replaced each year. In case of Korea, large number of wastewater treatment plants and sewers were constructed in 1990s and 2000s. The rate of population connected to public sewerage has reached up to 92 % in 2012 [4]. Therefore, the recent focus of the government is to increase qualitative level of sewer service rather than quantitative enlargement of the system. The requirement for systematic sewer asset management also has been raised from various sectors as a result of series recent experiences on urban (sewer) flooding events. It is also true that sewer infrastructures are managed on a worst-first basis, but this leads to ineffective funding allocations and more frequent system failures [5]. In order to plan effective strategies for sewer operation, maintenance and rehabilitation, it is important to provide methods and tools to support strategic planning.

The fundamental framework of asset management widely used in transportation area consists of seven components: (1) inventory of asset, (2) condition assessment, (3) prediction model, (4) decision making, (5) maintenance and rehabilitation, (6) prioritization, and (7) GIS visualization [6]. Once condition assessment and the prediction model are executed with the available data in well-prepared inventory, then municipalities have a comprehensive understanding of their infrastructure asset. This concept will lead to well-organized long term repair and rehabilitation strategies and optimized resource allocation for sewerage areas either.

Over the years, a number of studies was conducted to suggest a strategic framework and tools on asset management of civil infrastructure. In Canada, 'Best practices for utility-based data, a best practice by the national guide to sustainable municipal infrastructure' was published by the Federation of Canadian municipalities and national research council [7]. 'Asset management: a guide for water and wastewater systems' is one of the guidelines proposing efficiency in asset management [8]. A series of guidance were produced by US EPA including 'Asset management: a handbook for small water systems' and 'Asset management: a best practices guide' [9]. The most well known model in the sewerage areas is presumably the Computer Aided Rehabilitation of Sewer and Storm water Networks (CARE-S). This was carried out as a joint European initiative supported by the European Commission under the Fifth Framework Programme (EVK1-CT-2001-00167) for Research and Development. CARE-S is a decision support system including models and tools for the design and the exploration of rehabilitation strategies and programs for wastewater network, which proved its application in many studies [10, 11]. While CARE-S is powerful tool, it does not seem to be applied to every place where the existing rehabilitation methodology is conventionally used. If sewers are not repaired in time with perspective of integrated watershed management, it cannot consider the effect of the increased sewage treatment cost resulting from the inflow/infiltration (I/I) [12–14].

This study proposes a model for sewer asset rehabilitation planning. The model assumes the severity of defects in sewers would increase in time if not repaired. And this would result in the increased infiltration/infiltration flow as well as treatment costs. The optimization model in this study is to use one of the developed forms of genetic algorithm, called a fast messy genetic algorithm (fmGA) [15]. The GA already have had a known reputation in higher probability in converging to the global optimum [16, 17], and the fmGA has an improvement in solving large problems easily by adding building block filtering process. The specific strength of fmGA is rapid search in solving optimization problem [15, 18, 19]. The developed model was designed to find solutions for minimizing total costs of sewer rehabilitation and I/I treatment under limited budget. The model was tested in selected case study network of Banpo in Seoul, South Korea.

2 Model Developments

The sewer lines in a drainage basin can be divide into finite sewer sections between two consecutive manholes. The type of defects of each sewer section, i, is described as j. Depending on the number and extent of defects of each sewer sections, various repair options, k, can be applied to the existing sewers, which consist of sewer replacement after excavation, cured-in-place pipe lining process, and line grouting, and so forth.

To propose a decision strategy for optimal sewer rehabilitation planning for a long planning period, t_H, in a given drainage basin, several statements of problem are suggested prior to formulating the objective function and constraints as follows:

1. Present values of sewage treatment cost, sewer repair cost and maintenance cost are calculated by the single-payment and continuous compound interest method with the nominal discount rate, r_N.
2. The repair costs depending on various sewer repair methods and sewage treatment cost are estimated using the linear relationships having been used in the sewer rehabilitation projects actually implemented in parts of Seoul.
3. In order to select a sewer repair method to be implemented to each sewer, the existing algorithm MOSP is used [20]. MOSP is programmed to select one repair method considering the approximate repair costs of the currently available repair methods according to the predetermined judgment criteria using CCTV inspection data, which can be used to determine in this study the repair method k for the sewer defect j.
4. The either sewer sections does not have self-cleaning velocity or insufficient hydraulic capacity should be excavated and replaced.
5. Three types of costs are considered, namely treatment cost, repair cost and maintenance cost. The treatment cost are sum of sewage treatment cost and construction cost of wastewater treatment cost. Three repair options are applied to existing sewers depending on the number and extent of defects of each sewer sections. The cost for sewer replacement after excavation, cured-in-place pipe lining process and line grouting cost are the repair cost. The maintenance cost includes cleaning cost of each sewer.

6. Maintenance cost is estimated assuming that all the sewer sections are cleaned once a year to remove the sediments.
7. Design variables of the optimization problem are the sewer repair time, $\vec{t}^R = \left(t_{i,1}{}^R, t_{i,2}{}^R, t_{i,3}{}^R, \ldots, t_{i,p}{}^R\right)$, within a long planning period, t_H, in a given drainage basin. For instance, $t_{i,p}{}^R = 3$ means that the p-th repair on the i-th sewer line section is implemented in the 3rd year after the sewer rehabilitation is started.
8. The sewer repair is assumed to implement at the beginning of the repair time suggested by the model.

For $0 \le t \le t_{i,1}{}^R - 1$, the I/I of the i-th sewer at any given time t, $II_{t,i}$, is expressed as

$$II_{t,i} = \sum_{n=1}^{t_{i,1}{}^R} II_{0,i} \cdot \left(DR_i^{BR}\right)^n \tag{1}$$

where

$II_{0,i}$ average I/I of the i-th sewer at t = 0.

DR_i^{BR} rate of increase of the annual I/I due to the increase of defects in progress unless the i-th sewer is repaired.

For $t_{i,1}{}^R \le t \le t_{i,2}{}^R - 1$, we assume that the annual I/I could still increase at a rate of DR_i^{AR} as time goes by even after the repair is implemented.

$$II_{t,i} = \sum_{n=1}^{t_{i,2}{}^R - t_{i,1}{}^R} \left\{ II_{0,i} \cdot \left(DR_i^{BR}\right)^{t_{i,1}{}^R - dII_{t,i}} \right\} \cdot \left(DR_i^{AR}\right)^n \tag{2}$$

where

$dII_{t,i}$ reduced I/I resulting from the repair of the i-th sewer at time t.

DR_i^{AR} rate of increase of the annual I/I after the i-th sewer is repaired.

Thus, assuming that p_i—repairs using the same repair method are implemented on the i-th sewer due to the endurance period of the repair method, $II_{t,i}$ can be described for $\vec{t}^R = \left(t_{i,1}{}^R, t_{i,2}{}^R, t_{i,3}{}^R, \ldots, t_{i,p_i}{}^R\right)^T$ as

$$II_{t,i}(j_i;\vec{t}^R) = \sum_{n=1}^{t_{i,1}{}^R} II_{0,i} \cdot (DR_i^{BR})^n + \sum_{q=1}^{p_i} \left\{ \sum_{n=1}^{t_{i,q+1}{}^R - t_{i,q}{}^R} \left[II_{0,i} \cdot (DR_i^{BR})^{t_{i,1}{}^R} - dII_{t,i} \right] \cdot \left(DR_i^{AR}\right)^n \right\}$$

$$\text{for} \; t_{i,pi} \le t_H - 1 \tag{3}$$

If p_i—repairs are to be implemented in a planning period, t_H, then p_i—design variables for sewer i are required since $\vec{\mathrm{t}^{\mathrm{R}}} = (t_{i,1}{}^R, t_{i,2}{}^R, t_{i,3}{}^R, \ldots, t_{i,pi}{}^R)$. Because the condition of the sewer is deterministically unknown when sewer i is firstly repaired or at $t_{i,1}{}^R$, however, it is impossible to estimate values of the remaining $\left(t_{i,2}{}^R, t_{i,3}{}^R, \ldots, t_{i,p_i}{}^R\right)$. As an alternative, therefore, we are to assume to use the same repair method as the first-implemented repair on sewer i after the endurance period of each repair method. With this assumption, p_i —design variables decrease to 1 for the i-th sewer.

In order to minimize the sum of I/I treatment cost and rehabilitation cost, as a result, the sewer rehabilitation optimization model with design variables $\vec{\mathrm{t}^{\mathrm{R}}} = (t_{i,1}{}^R, t_{i,2}{}^R, t_{i,3}{}^R, \ldots, t_{i,p_i}{}^R)$ for $i = 1, 2, \ldots, n_s$ and $0 \le t_i{}^R \le t_H$ is summarized as discrete optimization problem with constraints as follows:

$$\text{Minimize: } TC_t(\vec{j}; \vec{\mathrm{t}^{\mathrm{R}}}) + \sum_{i=1}^{n_s} \left[RC_i(j_i; \vec{\mathrm{t}^{\mathrm{R}}}) + MC_i(j_i; \vec{\mathrm{t}^{\mathrm{R}}}) \right] \tag{4}$$

Subject to:

$$\sum_{i=1}^{n_s} \left[RC_i\left(j_i; \vec{\mathrm{t}^{\mathrm{R}}}\right) + MC_i\left(j_i; \vec{\mathrm{t}^{\mathrm{R}}}\right) \right] \le B_H \tag{5}$$

$$\mathrm{TC}\left(\vec{\mathrm{j}}; \vec{\mathrm{t}^{\mathrm{R}}}\right) = \mathrm{UC}_t^T \cdot \sum\nolimits_{\mathrm{i=1}}^{\mathrm{n_s}} \mathrm{II}_{\mathrm{t,i}}\left(\mathrm{j_i}; \vec{R}\right) \tag{6}$$

$$UC_t{}^T = UC^T \cdot e^{-r_N \cdot t} \tag{7}$$

$$\begin{aligned} II_{t,i}\left(j_i; \vec{t_i^{\mathrm{R}}} = \sum_{n=1}^{t_{i,1}^R} II_{0,i} . \left(DR_i^{BR}\right)^n \right) \\ + \sum_{q=1}^{p_i} \left\{ \sum_{n=1}^{t_{i,q+1}^R - t_{i,q}^R} \left[II_{0,i} . \left(DR_i^{BR}\right)^{t_{i,1}^R} - dII^{t,i} \right] . \left(DR_i^{AR}\right)^n \right\} \end{aligned} \tag{8}$$

$$RC_i\left(j_i; \vec{t_i^{\mathrm{R}}}\right) = \sum_{n=1}^{p_i} \left\{ UC_{ik}^R . e_N^{-r.t_{i,n}^R} . L_i \right\} \tag{9}$$

$$MC_i\left(j_i; \vec{t_i^{\mathrm{R}}}\right) = \sum_{n=1}^{t_H - p_i} \left\{ UC_i^M e^{-r_N . t^R} . L_i \right\} \tag{10}$$

where

t	time passed from the present
TC	present value of the wastewater treatment cost at time t
RC_{it}	present value of the repair cost implemented on sewer i at time t
MC_{it}	present value of the maintenance cost implemented on sewer i at time t
UC_t^T	present value of the unit cost of wastewater treatment at time t
U^T	unit cost of wastewater treatment at present ($t = 0$)
UC_{ik}^R	unit cost of repair k implemented on sewer i at present
UC_i^M	unit cost of maintenance implemented on sewer i at present
B_H	total budget (Korean won)
L_i	length of sewer i
n_S	total number of sewer

3 Model Applications—Description of the Study Network

A part of the sewer system within a subarea of Banpo in Seoul, Korea is selected to apply the model developed in this study. This sewer network system consists of 289 reinforced concrete circular pipes with diameter of 300–900 mm and 1 box-shape culvert of 3.5 m widths and total length of 10,652 m. It serves an area of approximately 57.21 ha with a population of 7,870. The schematic diagram of the sewer lines in this subarea is shown in Fig. 1.

Fig. 1 Layout of sewer lines of selected case study network

4 Rehabilitation Strategy Planning

4.1 Rehabilitation Planning for Individual Sewer Lines

The change of sewer rehabilitation cost for a planning period of 20 years is computed, as shown in Fig. 2, as the available budget may increase from 0 to 50 billion wons. The rehabilitation cost of 14.5 billion won at zero budget results from the cost of excavation and replacement of sewers with hydraulic capacity less than demanded and in need of their slope correction at $t_i^R = 0$. As budget increases, the rehabilitation cost attains at approximately 15.7 billion won, suggesting that it can be used as temporary budget for future rehabilitation planning.

The costs required to implement the sewer rehabilitation program in the subarea are estimated by executing the model with the discount rates of 5 % for each of the following 4 cases.

Scenario I: No sewer rehabilitation is implemented in a planning period of 20 years.
Scenario II: All sewers are repaired at the beginning of the final year (t = 19).
Scenario III: Only the sewer lines lack of hydraulic capacity and hydraulic gradient are repaired at t = 0.
Scenario IV: Optimized sewer rehabilitation using the pseudo-optimal budget.

The above scenarios may be evaluated depending on the financial status of a local government and the preference of policy makers. Table 1 shows the rehabilitation costs and I/I treatment costs of each case above and compares the effects of the optimization. As for scenario II, since the sewer rehabilitation is postponed for 20 years, additional 11.6 and 17.6 billion won should be expended for the sewer rehabilitation and I/I treatment. The total wasteful expenditure is 29.2 billion won,

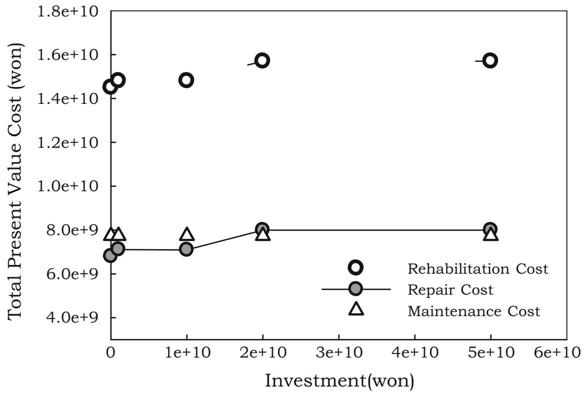

Fig. 2 Change in the total rehabilitation costs

Table 1 Effects of investment for different rehabilitation scenarios (unit: billion wons)

I/I treatment			Sewer rehabilitation				
Scenario and comparison	I/I treatment cost (A)	Savings in I/I treatment	Cost of replacement of critical sewers at t = 0 (B)	Maintenance cost (C)	Repair cost (D)	Rehabilitation cost (E = B + C + D)	Total cost (A + E)
I	37.5	–	–	7.7	–	7.7	45.2
II	$34.2^{(1)}$	3.3	–	7.7	19.2	$26.9^{(4)}$	61.1
III	$28.3^{(2)}$	9.2	2.9	7.7	–	$10.7^{(5)}$	39.0
IV	$16.6^{(3)}$	21.2	2.9	7.7	4.7	$15.3^{(6)}$	31.9
II and IV	Additional expenditure for I/I treatment relative to IV = (1) − (3) = $17.6^{(7)}$ Additional expenditure for sewer rehabilitation relative to IV = (4) − (6) = $11.6^{(8)}$ Total wasteful expenditure = (7) + (8) = 29.2						
III and IV	Additional expenditure for I/I treatment relative to IV = (2) − (3) = $11.7^{(9)}$ Additional expenditure for sewer rehabilitation relative to IV = (5) − (7) = $-4.6^{(10)}$ Total wasteful expenditure = (9) + (10) = 7.0						

compared with scenario IV, suggesting that postponing the implementation of a sewer rehabilitation project for 20 years can lead to tremendous loss due to the increase of I/I treatment cost as well as rehabilitation cost. Although, in scenario III, additional 4.67 billion won is required compared with scenario IV, total wasteful expenditure is 7.1 billion won since scenario III needs greater expenditure for I/I treatment than scenario IV by 11.7 billion won. With comparison of several scenarios for sewer rehabilitation, it can be seen that the sewer rehabilitation should be implemented by optimization techniques.

4.2 Rehabilitation Planning for Group of Sewer Lines

It is rather unrealistic to repair individual sewer lines of different locations at a time. The common practices are to categorize the sewers required for the rehabilitation into groups and priorities the rehabilitation schedule for the group of sewer lines instead of selecting individual sewer lines. Sewers in the study area were classified in 34 groups considering the location of each sewer and accessibility in conduction the rehabilitation work first. Five year term of the 20 years (0–4, 5–9, 10–14 and 15–19 years term) was considered as the planning period. Every sewers lack of hydraulic capacity and hydraulic gradient are repaired at t = 0 in this case. The available budget applied was the same with that of planning for individual sewers (15.7 billion won). Among the 34 groups, selected numbers of groups required for rehabilitation for the four term period were 8, 10, 9 and 7 respectively. The total rehabilitation costs and I/I treatment costs for the whole planning period, 20 years, were also estimated from the model as 12.8 and 15.1 billion won respectively. Comparison to the planning for individual sewer lines, the rehabilitation planning for group of sewer lines suggested 0.4 billion won of additional expenditure, but the efficiency in the rehabilitation works are expected. Table 2 summarized the results of rehabilitation strategy suggested for group of sewer lines.

Table 2 Suggested rehabilitation strategy of groups of sewer lines for different planning period

Planning term	Selected number (and sewer groups) for rehabilitation	Total rehabilitation cost (billion won)	I/I treatment cost (billion won)
0–4	8 (1, 2, 9, 10, 15, 22, 30, 31)	3.1	7.0
5–9	10 (13, 14, 21, 23, 24, 25, 26, 27, 28, 33)	3.6	2.0
10–14	9 (3, 5, 7, 11, 12, 18, 19, 20, 29)	3.9	3.8
15–19	7 (4, 6, 8, 16, 17, 32, 34)	2.3	2.4
	Sum	12.8	15.1

5 Conclusions

Sewer rehabilitation for reduction of I/I has been recognized as a project requiring optimization, which needs an enormous budget for a long planning period. The mathematical model was formulated to compute I/I with or without implementing one of several repair methods on each of the sewers in any time in a planning period. A fast messy genetic algorithm was refined to take into account the optimization of existing sewer rehabilitation to minimize the sum of sewer repair cost and treatment cost in sewage treatment plant considering the rate of the I/I. It is shown that the model can be effectively used to estimate the optimal budget for a planning horizon. The model application both for the rehabilitation strategy planning of individual sewer lines and grouped sewer lines were successful. With comparison of several scenarios for sewer rehabilitation, it was found that the sewer rehabilitation could be beneficially implemented by optimization techniques. Using the model suggested in this study, city officials and engineering consultants as decision makers could have the broader perspectives and to consider various options of policy and design strategy in planning and implementing the sewer rehabilitation. Also, this model can act as a supplemental tool for asset management of sewer infrastructure.

Acknowledgments This research was supported by the Korea Ministry of Environment under Project 414-111-001.

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Methods and Tools for Sustainable Manufacturing Networks—Results of a Case Study

Teuvo Uusitalo, Helena Kortelainen, Padmakshi Rana, Susanna Kunttu and Steve Evans

Abstract Manufacturers need be proactive, innovative and operationally efficient to succeed in the current business environment. The transition toward sustainable manufacturing requires new approaches in the design, manufacture and use of products and services. These approaches need to take into account the network of stakeholders who influence and can be influenced by the sustainability of the product in the course of its life cycle. This paper presents results of a case study that used and tested methods and tools developed for creating a sustainable business model for a manufacturing company. The main research questions addressed here are: how to develop a sustainable business model; and how to explicitly illustrate to potential customers the life cycle costs of different solutions.

Keywords Sustainability · Asset life costs · Servitisation

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_7

1 Introduction

The transition towards sustainable manufacturing will require significant shifts in the design, manufacture and use of products and services. Initiatives till date around eco-efficiency, eco-innovation, waste management, and social responsibility are helpful but incremental and limited in their ability to drive system wide changes. As suggested by [10], 'companies must design products for longevity and ease of recovery at end-of-life, and must consider the business potential of processing used products to harness the residual value in their components'. Reference [5] recommended 'new strategies and solutions to obtain a better overall performance of high-tech engineering and manufacturing assets'. This would enable longer equipment life cycles and higher performances in respect to resource and energy consumption, product quality and equipment availability, achieved 'through effective and efficient maintenance, making this enterprise function an important issue for sustainability'.

To succeed in an ever-changing business environment, manufacturers must be proactive and innovative as well as operationally efficient [7, 8]. The industrial companies are increasingly confronted with demands to consider environmental and social aspects next to financial results. For manufacturing companies' competitiveness, development toward sustainability can bring new means of differentiation, and operations and growth related benefits and new business opportunities. Recent studies also help to understand the importance of non-tangible assets [6] and elements of sustainability [13] as a source of competitive edge.

Sustainability is driven mainly by the need for regulatory compliance, cost savings through eco-efficiency, corporate social responsibility initiatives, and satisfying customer demand. While important, these approaches have not generally embedded sustainability into the core of the business and become part of an integrated solution, and as such their impacts are often limited. For many companies sustainability remains at the level of PR, expressions in strategies and branding, if it is considered at all. Moreover, the inter-connected nature of the world—multiple networks of stakeholders and inter-relationships between different industries through product use and disposal phase requires a long term vision and holistic solution focusing on redesigning business models for sustainability to co-create multi-stakeholder value. As Krantz [11] proposes 'companies will need even bigger changes, including new business models, greater trust, and greater stakeholder engagement' based on a 'long-term vision' for pursuing sustainability.

A transition towards sustainability will be possible only with strategies and policies that recognize business as a part of the solution and create the right incentives, enabling the manufacturing industry to adapt and remain competitive [27]. Such a transition means a significant shift in the way businesses are conceived and operated through collaboration amongst stakeholders in the value network. More specifically, this requires emphasis on business models that deliver sustainability not only through incremental social and environmental initiatives, but by actively addressing the problems from a multi-stakeholder approach that deals with network interdependencies and complexities across company, industry and global levels.

Sustainable business models (SBM) incorporate economic, environmental and social aspects of business and consider a wide range of stakeholder interests. The objective of a sustainable business model is the harmony of stakeholders' interests to ensure broader positive value creation for sustainability. Key authors who have articulated a business modeling process and defined the components of a business model (value proposition, creation, delivery and capture) include [16, 20, 24, 29]. Their focus has not been specifically on delivering sustainability, but they provide an extensive overview of the current state-of-art and state-of-practice. References [1, 2, 14, 15, 18, 21, 23, 25] amongst others have contributed to academic and industrial research on business models, concepts and strategies for delivering sustainability. However, there is still a need for further clarity on the sustainable business model design process and supportive tools that will provide companies with a holistic solution to create, transform and implement sustainable business models.

Major part of the product life cycle costs as well as environmental impacts over the whole product lifecycle is defined by the decisions taken in the early concept and design phase. Often the acquisition price comprises only a minor part of the total cost of ownership (e.g. [4]). However, most business-to-business (B2B) negotiations concern only purchasing price and do not take the product's whole life cycle costs and effects on the environment into account (e.g. [13, 22, 26]). One reason for this is the lack of practical tools to calculate and show estimates of the life cycle costs.

The processes, frameworks and tools proposed by the leading authors all have merit and provide sound basis for sustainable business modeling. Nonetheless, an enhanced and simplified process and set of tools that better integrates the business model concept with sustainability is considered necessary. Hence, the sustainable business modeling process and some of the supportive tools[1] used and discussed through the results of a case study—manufacturing company in this paper is expected to support the analysis and design of sustainable business model/s.

This paper, in particular investigates:

i. how to develop sustainable business model.
ii. how to transparently show to potential customers the life cycle costs of different solutions.

The paper first presents the methodology—the case company and the methods and tools used in the case study followed by findings from the case study. The last section discusses the results of the study.

[1] Identified and developed in the Sustain Value project http://www.sustainvalue.eu/publications/D2_6_Final.pdf.

2 Methodology

The objective of the case study was to develop sustainable business model and to improve the company's offering of sustainable solutions. The case company is a small company providing power supply systems to the energy, ICT, transport and process industries. The battery back-up systems are necessary to guarantee 24/7 operation of critical devices also in any failure situations of the electrical mains network. Battery back-up DC power supply system solutions are being used in many power plants and stations, substations and other locations, including e.g. uninterrupted power supply of process automation. The case company's products are typically customized solutions for its B2B customers who are project suppliers of larger systems and integrate the solutions delivered by the case company into their own offerings to end-users.

The case study was carried out in a series of workshops to assist the case company in understanding, developing and applying the new value proposition and sustainable business model. Life cycle cost estimation (LCC) tool was developed to be utilised in the delivery project negotiations with potential customers to explain higher purchasing price with lower life cycle costs and more sustainable solutions. The methods and tools used by the case company were the following:

i. Sustainable Business Modelling (SBM) process;
ii. Corporate sustainability continuum;
iii. Value mapping tool;
iv. Business model canvas;
v. Life cycle cost (LCC) estimation tool.

These methods and tools are described in the following paragraphs.

To support companies in developing sustainable business modelling a five-step SBM process is developed. This process considers a network-centric perspective to deliver sustainability ([9, 19]). The SBM process accompanied by a portfolio of tools provides companies with assistance in the analysis and design of sustainable business models for network level change. This approach introduces the sustainability dimensions (environmental, social and economic) and priorities, language around multi-stakeholder value and shared-value creation across the industrial network and harmonizing stakeholder objectives through the identification of conflicting interests between them. The process is iterative, in that as changes occur in one step it not only impacts on the following step but also on the preceding ones and occurs over a period of time. Companies can be at various stages of the SBM process so using the process and toolset will rely on the preference of the participants.

Corporate sustainability continuum [28] represents the progress of a company on the path towards sustainability. It supports companies in reviewing their current and future path towards sustainability.

Value mapping [3] is a tool designed to help companies to create value propositions to support sustainable business modelling. The tool builds on four value forms—captured, destroyed and missed and opportunities with a multi-stakeholder approach. The tool has the following specific aims:

- Understand the positive and negative aspects of the value proposition of the value network (i.e. the network of stakeholders involved in creation, delivery and receipt of value associated with provision of a product/service)
- Identify conflicting values (i.e. where one stakeholder positive benefit creates a negative benefit for another stakeholder), so that action can be taken to tackle these
- Identify opportunities for business model redesign and realignment of interests to reduce negative outcomes and improve the overall outcome for the stakeholders in the value network—especially for society and the environment.

The business model canvas [16] supports companies in the coordination and configuration of the value network. The canvas attempts to capture all the dominant components of the business model (value proposition, creation, delivery and capture) and is made up of nine building blocks—value proposition, customer segments, channels—describes how a company communicates with and reaches its customer segments to deliver a value proposition, customer relationships, revenue streams, key resources, key activities key partnerships and cost structure. The canvas was not specifically designed for sustainability but as it addresses the key components of a business model, it is considered helpful to configure the value network for the sustainable value proposition/s and associated business model/s.

Life cycle cost (LCC) analysis is a method to calculate or estimate all costs from the beginning of product/system life to the end of life. In principle life cycle cost calculation is a simple method. It just sums up all relevant cost factors. Calculation of basic key performance indicators, like net present value of costs, is also well established. Life cycle profit (LCP) analysis is another well-known method which considers also profits in addition to costs. In this case life cycle cost calculation method was selected because the nature of the case company's products is about achieving cost savings by guaranteeing uninterrupted supply of electricity [12].

Analysing life cycle costs is not without challenges. The first challenge is to establish a cost structure which includes all relevant cost factors and their effect on total life time cost of the product/system in question. Another challenge concerns the availability of data for cost factors. Especially, if LCC analysis is done in the early phases of a life cycle uncertainty about the future costs related to the end of the life cycle is high. Applying LCC analysis in practise can be a challenge, too. It is possible to make calculations by 'pen and paper' but performing the analysis in that way is time consuming. Thus a tool supporting LCC analysis is needed and the developed LCC tool strives to tackle the aforementioned challenges.

3 Results of the Case Study

Application of the different methods and tools provided the case company with new understanding about their business model as well as their products. Structured information concerning business models and their elements enabled representatives of the company to analyse their prevailing business model which was the first step of business model development process. The following subsections detail the results from the case study.

3.1 SBM Process and Tools—Value Mapping Tool and Business Model Canvas

The SBM process and tools were used in a workshop session to assist the company with their business modelling approach. The workshop session raised the need to update the case company's mission and vision. The company representatives considered that a new vision and mission would be important and guide the company's next steps, potentially towards a new form of service offering. The company was observed to have a problem solving approach. Developing an explicit business modelling process to assess its performance was considered useful. As a result of the workshop the following steps to guide the company's further work on developing a sustainable business model was generated:

i. Define the mission and vision
ii. Identify new partners and collaborations—global market expansion
iii. Focus on a particular value proposition for example 'new service offering'
iv. Adopt collaborative models for developing stakeholder engagement and improving customer relationships (customer selection, opportunity to generate new business from customers)
v. Develop financing structure—cost and revenue model and network.

The value mapping tool generated new ideas for exploring the service offering for the company such as new offerings in monitoring facilities and equipment, new revenue streams through lease (in addition to one-off sale) and revenue through reuse. The use of the tool further emphasised the positive impact of using shared infrastructure and resources for improving communication of production and delivery stages and being cost effective. The results of the use of the value mapping tool are summarised in Table 1.

The use of the business model canvas assisted the case company in configuring the new value proposition with the potential new business model—selling service. Configuration of the various business model elements on the canvas such as activities, resources, partners, sales channels and customer segments, provided the

Table 1 Results of the value mapping tool

Stakeholders	Value captured	Value destroyed value missed	Value opportunities
Society	Support regional development—employment, improved living standards	Relocation due to changing business structure and expansion	Job creation
	Access to clean technology	Loss in tax money due to business failure	Business growth may lead to investments in society—education, infrastructure
Environment	Development of a technology with positive impact	Higher energy use in storage	Clean air and technology
		Technical risks in design, assembly and manufacture	
	Utilisation of green technology	Recycling and reuse of equipment	
Customers (B2B)	Ease of use	Unable to deliver the committed products and services	Ability to focus on their core business rather than products
	Long term investment in the infrastructure		
	Provision of life cycle costing and analysis	Fuel price and government policies not favourable for the business	Economic—potential for cost effectiveness
	Ensure functionality for their operations	Extra investment due to use of wind and solar, natural calamities	
	Reduction one off investment cost – monthly fees	Change in ownership contract	Compensation for loss of energy
		Commitment to one supplier	
End users	Ease of use as it comes with the infrastructure—sleeping better, insurance	Unable to deliver the committed products and services	No loss of power—assurance for business functioning without power cuts
	Product quality—avoid frequent maintenance issues	Fuel price and government policies not favourable for the business	Less power generation instability
	Minimisation of risk—service offering	Extra investment due to use of wind and solar, natural calamities	Focus on the core business
	no extra costs	Change in ownership contract—cost	Compensation for loss of energy
Investors and shareholders	New offering—potential for improved and stable economic return	Negative impact of natural calamities on the equipment; new regulations that are difficult to comply to	New offering and opportunities
			Economic return;
		Suppliers unable to deliver or moving away—have multiple suppliers to hedge the risk	Increase in brand and image value

(continued)

Table 1 (continued)

Stakeholders	Value captured	Value destroyed value missed	Value opportunities
		Economic risk of the business, customers going bankrupt	
		Larger companies, with more resources and aggressive strategy	
Employees	Stability as the company has regular income	New expertise required	More job opportunities and career progression
	Part of an innovative company	Seasonal work—when projects are available	Better benefits and facilities—training
Suppliers and partners	Minimised risk—shared technical and financial risk	Customer volumes not realisable	New business opportunities for existing suppliers
	Focus on core competencies in their area	Business loss due to compatibility issues with the company's new offering	
		Potential change in supplier relationships—unable to change their priorities with the new product	Need for maintenance suppliers—measuring systems
		Risk due to change in business—use of the competitors' products	

company with insight into strategic and operational changes and arrangements required. Below is a summary of the outputs from the use of the business model canvas (Table 2).

3.2 LCC Estimation Tool

The practical implementation of LCC calculations has been done by MS Excel 2010 application (see [12, 17]). Excel was selected because it is widely used and does not require any new IT investments. Another reason for selecting Excel is that a prototype tool could be developed with reasonable work.

All calculations implemented into the LCC tool are done in Excel worksheets. To make the tool more user-friendly separate forms for data input and result examination were also developed. Forms were created by Excel VBA programming language. Although data input and result examination are possible without form

Table 2 Results of the use of the business model canvas

Business model canvas area	Results
Value proposition	Service offering: differentiation strategy, continuous income, clean technology, competitive advantage
Customer relationships	Develop direct contact with new customers; Customer retention, find new customers; Change in sales pitch—involve the customers, selling only the functions; Improve feedback loop, value co-creation with network partners (customers); Improve awareness and information on existing and new products
Customer segments	Construction companies; Shopping centres (outside Finland); Hospitals; Data centres; Service providers
Channels	Monitoring (control) for technical feedback, e.g. care of the cooling system; Feedback loop—information flow on the use through the customers; Develop direct contact with new customers, awareness of the new offering; Customised agreement—purchase; Use their own delivery of the instalment company
Key activities	Servicing and monitoring are key activities; Finding new customers—sales and marketing; cost for lease; Service offering new solution
Key partners	New suppliers and partners for maintenance; Existing partners alliance to be continued, while generating more business opportunities; Continue sharing infrastructure and resources with the switch board and installation companies—facilitates communication
Key resources	Maintenance—monitoring and measuring equipment; Local office or a partner for global location of equipment; service contract—agreement for lease with customers; Human resources—more staff in the technical support team; Intellectual resources—patents (thought in process); Financial resources—investment through customers buying the service followed by moving to the market, increase in sales
Cost structure	Monitoring equipment; New staff and suppliers; Expand in the existing site (future); Value driven business—cost incurred, time and resources required
Revenue streams	Leasing agreement based on individual customer; Monthly payment structure; One off payment; reuse of equipment for further revenue based on the condition after testing for shorter contracts—effective use of resources, components reconfigured or reused, dismantle to smaller units

interface, it was implemented into this prototype because the user-friendly interface facilitates substantially better real user tests.

Regarding their products, representatives of the case company had the assumption that purchase price would not be the biggest cost category of the total life cycle costs. This assumption was strengthened along the progress of LCC tool development work and data collection. It was actually a surprise how small the proportion of purchase price is compared to total life cycle costs. It is not an exception that the purchase price is less than 5 % of the estimated total life cycle costs. This insight is a significant driver in moving toward new business models as it shows the scale of importance for the customer.

At the beginning of the development work the focus was to support the case company's customers' investment decision making. During the LCC tool development and testing, it was realised that the calculation can also elicit ideas to improve products from the life cycle perspective. The tool can reveal items with insufficient life cycle performance and that should be replaced with components that lead to better overall results (Fig. 1).

The LCC tool till date is at the test phase and was used in the preparation of a few offers so there is no proof yet of the company receiving new orders or new customers by applying the new tool. Main benefits of the tool will be achieved in the future when the tool will be fully exploited in the negotiations with customers and in the development of own product portfolio.

Fig. 1 Example of the results of a LCC analysis

4 Conclusions

The SBM process and related tools resulted in the following for the case company:

- Generating cross organisational views—multi-stakeholder view
- Broaden thinking and formalise ideas for the new offering, which consequently generated thoughts for the company’s existing business
- Stimulating pathways and options for transforming the business
- Facilitation and prompt questions helped to generate broader thinking and providing guidance
- Encourages openness and change across the company.

The representatives of the case company have new understanding about sustainable business models and assessment of sustainability of their own products through the application of the SBM process and tools. Based on this information there has been concrete operational arrangements and also changes in ways to think and discuss about sustainability of products.

The implementation of the new business model also brings new challenges to the company’s every-day operations. In order to respond to its value proposition, operational arrangements were made and new requirements for product development were identified. In this case operational changes were accomplished by networking with another manufacturing company. In this new setting the case company’s responsibilities are in operations related to sales, services, product and service design and development while their partner is responsible for the manufacturing of the products.

The further application of the results from the workshop, will involve the following for the case company:

- Use the results for future meetings on business concept generation, internal meetings and analysing existing business operation
- Transforming the new value proposition—future task for the company
- Use the tools (value mapping tool and business model canvas) with the board, staff, suppliers and customers of the company
- Potential for the value mapping tool to be used as a feedback tool
- Customer specifications for product improvement.

The development process of the LCC calculation method and tool has also been a learning process to the company’s personnel. LCC calculation provided a means to communicate company’s value proposition to their customers. The main result achieved so far is that the case company has gained reputation as a company with a true interest in sustainability issues. Customers have considered it valuable that the company has taken very concrete steps towards sustainable business. The customers had not seen a corresponding tool being used by other companies even though the importance of life cycle costs as decision criteria is very often mentioned in their brochures. Customers have been pleased that the case company has actively developed a concrete tool to support open discussion about sustainability and life cycle costs.

The developed LCC tool was a first prototype and the tool still needs development before all benefits from the method are achievable. Main plans about the tool concern ideas to develop a web service based on the developed tool combined with a database. With a web service customers would be able to make their own calculations and comparisons which can be a competitive advantage for the company because their competitors currently fail to provide corresponding services.

The overall SBM process and tools are envisaged to have use and applicability to all sustainable business modelling activities, whilst providing support at strategic and operational levels of the companies to deliver sustainability, as demonstrated through the case study. A key consideration in the use of the methods and tools demonstrated in this paper is assisting companies in understanding the true scope of the impact of their activities on the broad range of stakeholders and identifying possible pathways to adaptation, while persuading companies to adopt sustainability, when the business case is not very clear. A transformation and implementation path towards sustainability will follow a long-term vision with an evolutionary path, which needs to be considered when using the methods and tools.

In summary, the SBM process and tools will continuously evolve through its use in different business environments and scenarios. Hence, future work on enhancing and updating the SBM process and toolset with new tools, methods and frameworks, which have a network centric approach based on the emerging requirements for companies integrating sustainability into their purpose and activities is anticipated.

Acknowledgments The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7, 2007–2013) under grant agreement 262931. The authors wish to acknowledge the European Commission for their support and the case company for their contribution to the study.

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Part II
Condition, Risk and Vulnerability Assessments

A Modeling Approach for Infrastructure Evaluation from Customers' Viewpoints: Using Sewer Systems as a Case Study

Byongjun Kang, Soonyu Yu, Hyungjoon Kim and Kyoo-hong Park

Abstract Even though sewer system is an important social infrastructure for the sewage collection, rainwater discharge, public health, flood prevention, and amenable environment, the concern of the end-users of wastewater system is lower than in other infrastructures because most sewers are buried below ground level. The evaluation on the customer satisfaction for wastewater service has rarely been carried out, since it belongs to an expertise field in which many public officials believe the municipality-led management is necessary. In this study, customer satisfaction for wastewater service is evaluated by customer service modelling approach applying structural equation model. As a result, sewerage service quality and improvement of environment affect customer satisfaction. In case of the sewer service quality, odor and clogging are relatively more important than flooding, meaning customers are more interested in their neighboring environmental concerns and inconvenience. The effect of sewerage service quality on surrounding environment is significant, while the effect of environmental improvement on customer satisfaction is relatively small. Customers do not seem to have the willingness to accept the increased sewerage fee even if the sewerage quality and environment are surely improved from the current state.

1 Introduction

For the recent several decades in Korea, many sewerage facilities have been constructed nation-widely as demanded and the rate of population connected to public sewerage reached up to 92 % in 2012. In the meantime, the importance of effective management, operation, and maintenance of the existing sewerage facilities has been emphasized. The necessity of asset management implementation on social

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_8

infrastructures under a new institution in near future is being recognized among many experts. In perspective of wastewater asset management, Korean Ministry of Environment (KMOE) intends to focus more on increasing the qualitative level of service rather than on the quantitative enlargement of wastewater service. It has used many performance indicators to evaluate wastewater service from managerial viewpoints [1], but not from customers' viewpoints.

The performance indicators (PIs) have also been developed by International Water Association (IWA) to provide comprehensive management tools for undertakings and other stakeholders involved in any aspect of wastewater service provision [2]. In conducting the project funded by the 5th EU framework program, reference [3] also suggested based upon IWA PI system that a tailored set of PIs could be selected within CARE-S: operational indicators, physical indicators, environmental indicators, quality of service indicators, financial indicators. The service quality indicators consist of the number of flooding affecting properties, interruption or blockage of sewage flow, and the number of complaints, while the economic and financial indicators are related to cost (total cost and operating cost) and installation for new assets and replacement and renovation for old assets. If customers are not satisfied with the utility service due to the troubles resulting from the aging water and wastewater infrastructures and the untimely investment for their renewal and rehabilitation, they might hesitate or be reluctant to pay their environmental fee (including sewer fee and so on).

It is important for service providers to measure the level of satisfaction among customers, as this could assist providers in identifying and reforming the areas that may need improvement. Meanwhile, investigative issues related to the improvement of customer satisfaction have long been a major area of research in the service marketing subfield of business management. Though, in non-competitive public wastewater service market, the marketing strategy has not been so important, the situation becomes different in increasing privatized water and wastewater service market in worldwide. Accordingly, the understanding on the satisfaction of customers who pay for the service is getting important in achieving the ultimate goal of full cost recovery to pay for new infrastructure assets, working capital, environmental and resource cost, maintenance and renewal of aging assets, and operating costs.

American Customer Satisfaction Index (ACSI), developed in the mid-1990s, for instance, has provided a basic framework for many other index models created elsewhere in the world [4, 5]. However, the related studies have been mostly focused on measuring customer satisfaction indices for entire industry sectors, and the rankings produced have been used for the purpose of advertising the concerned sectors and marketing. Especially, water and wastewater service evaluation from customers' viewpoints has been rarely conducted, except for recording only the number of complaints, hours or days to cope with the complaints, and so on.

In this study, we propose a new customer satisfaction index (CSI) model which is adapted to the field of wastewater service. By calculating the index, the study can offer the providers of this service with practical tips which will result in an improvement in service quality.

2 Theoretical Background and Hypotheses

2.1 Theoretical Background

2.1.1 Customer Satisfaction Index Models

The ACSI model was started in the United States in 1994 by researchers at the University of Michigan in conjunction with the ASQ [5]. The ACSI model was derived from a model originally implemented in 1989 in Sweden called the Swedish customer's satisfaction barometer (SCSB). This is an economic indicator that measures the customer's satisfaction across the U.S. economy. Research groups, quality associations and universities in several countries have adopted the ACSI model to create customer's satisfaction indices for their own national economies.

The ACSI model is a cause-and-effect model with indices for drivers of satisfaction on the left side (customer expectations, perceived quality, and perceived value), customer satisfaction (ACSI) in the center, and outcomes of satisfaction on the right side (customer complaints and customer loyalty, including customer retention and price tolerance). This is to say, the higher the customer expectations, the higher the perceived quality; the higher the customer expectations and the higher the perceived quality, then the higher the perceived value, which finally results in higher customer satisfaction. Likewise, a high level of customer satisfaction tends to reduce customer complaints and increase customer loyalty. Thus, the causal model explains the inversely proportional relationship between customer complaints and customer loyalty.

The European Customer Satisfaction Index (ECSI) model uses six constructs, namely, image, customer expectations, perceived quality of hardware and software, perceived value, customer satisfaction, and customer loyalty. These six factors are also linked through a causal relationship. Image has a determining influence on customer expectations, and customer expectations, in turn, affect the perceived quality of hardware or software. The ECSI model eliminates the category of 'customer complaints' present in the original ACSI model [6].

The Swiss Index of Customer Satisfaction (SWICS) measures three factors: customer satisfaction, customer dialogues, and customer loyalty. The three factors exist in a causal relationship in which customer satisfaction affects customer dialogue and customer loyalty, and customer dialogue affects customer loyalty [7].

These CSI models reveal that most of them could be improved through the use of more detailed perceived quality factors. The obvious reason for this is that, as has been pointed out by many studies, a high level of customer satisfaction reduces customer complaints and increases customer loyalty; therefore, it is of paramount importance to improve customer satisfaction, which can be achieved by enhancing the level of perceived quality. Quality-related factors are also as important with regard to wastewater service as to other product manufacturing or services. By determining which quality factors are capable of increasing customer satisfaction and developing strategies for quality improvement, service providers can improve the odds of the successful commercialization of these services or reduce complaints among customers in implementing full cost recovery policy with wastewater service.

2.1.2 Quality Factors in Wastewater Service

One of the most important perceived quality factors for customers of wastewater services is the recognition of wastewater collection service. The main function of a sanitary sewer system is to convey wastewater and solid waste from homes, businesses and industries through a series of underground pipes and manholes to wastewater treatment plants where it is cleaned and returned to the environment. The storm sewer system collects rain and melting snow, referred to as runoff, in catch basins set alongside roadways. The runoff flows through pipes and manholes connected much like the sanitary system. This water does not require any treatment and is diverted directly to local streams and waterways. There is also a third type of sewer system called a combined sewer. In this system, one pipe carries both sanitary wastewater and storm runoff together. In this study, we selected three main problems resulting from sewer systems; sewer flooding, sewer backups, and sewer odors.

Another important quality factor of wastewater collection and treatment system is to maintain clean urban environment and good quality of receiving water to which the treated wastewater is discharged.

The third quality factor is interaction with customers. In [3], complaints on blockage, flooding, pollution incidents, and odor was selected as the final PI list established for the CARE-S and recorded in the unit of No./1000 inhabitants/year. 'Interactivity' is one of the system quality factors affecting satisfaction with a customer support system. The target level of service at OCSD with respect to interactivity with customers is that 90 % of public complaints or inquiries regarding construction projects should be responded within 1 working day and 90 % of new connection permits should be processed within 1 working day [8].

Finally, the fourth factor is related to tariff. Sewerage fee which customers should pay for wastewater service must affect customer satisfaction very much. If the wastewater service quality is not satisfactory relative to the sewerage fee they paid, they will be reluctant to pay for it. When the local government or its partners intend to increase the sewerage fee as the old wastewater infrastructure ages and new investment is needed, they may have difficulty in persuading customers who has not been satisfied with their service. Unless wastewater tariff is paid by customers in the sense of full cost recovery or at least sustainable cost recovery, it will cause the expense of revenue, resulting in complicated social problems in other fields. The quality factors affecting customer satisfaction in wastewater services are summarized in Table 1.

Table 1 Latent variables and measurement variables used in the proposed CSI model

Latent variables	Measurement variables
Sewer service quality	1. Prevention of sewer flooding
	2. Prevention of clogging and backups
	3. Odorless sewerage
Interactivity with customers	4. Operation of 'hot line' to receive complaints from customers
	5. Counteractions after receiving complaints on sewerage service
Sewerage fee	6. The level of sewerage fee that customers pay
Customer satisfaction	7. Overall customer satisfaction with wastewater service
Customer complaint	8. Submission of complaints on wastewater service
Customer loyalty	9. Customers' willingness to accept the increased sewerage fee
Clean environment	10. Maintaining good quality in receiving water
	11. Maintaining clean urban environment

2.2 Customer Satisfaction Index Model for Wastewater Service and Hypotheses

To increase the level of satisfaction felt by customers of wastewater services, reduce complaints, and thereby enhance their loyalty to the service provider, we identified a series of perceived quality factors that influence customer satisfaction and proposed a primary CSI model as described in Fig. 1. The quality factors deemed in this model to positively influence customer satisfaction are the following: the quality of sewer service, the quality of environment, interaction with customers, and sewerage fee. Customer satisfaction, customer complaints, and customer loyalty form a causal chain of relationships. In other words, a high level of customer satisfaction decreases customer complaints, and the decrease of customer complaints, in turn, results in enhanced customer loyalty. In this study, customer loyalty means that customers are willing to allow the sewerage fee to be increased. In this study, we formed the following hypothesis;

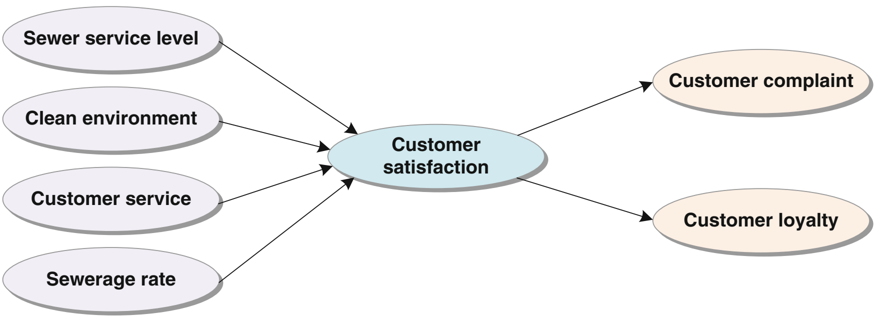

Fig. 1 The primarily proposed model for customer's satisfaction index for wastewater services

Hypothesis 1: The quality of wastewater collection service offered through sewer system has a positive effect on customer satisfaction with wastewater service.

Hypothesis 2: Clean urban environment and the quality of receiving water body to which treated wastewater is discharged have a positive effect on customer satisfaction with wastewater services.

Hypothesis 3: Interaction quality with customers has a positive effect on customer satisfaction with wastewater services.

Hypothesis 4: Low sewerage fee has a positive effect on customer satisfaction with wastewater services.

As suggested by the ACSI model, customer satisfaction has a negative influence on customer complaints and a positive influence on customer loyalty.

Hypothesis 5: Customer satisfaction has a negative effect on customer complaints about wastewater services.

Hypothesis 6: Customer satisfaction has a positive effect on customer loyalty about wastewater services.

3 Research Methods

The questionnaire items used in the survey were tested through a preliminary survey, which was conducted with technological experts and business professionals involved in the field of sewerage facility design and operation. After the necessary modifications, the 11 questionnaire items shown in Table 1 were finally selected. All of the items were measured using a 9-point scale (1: very low, 9: very high).

Three places were chosen for asking questionnaire as shown in Table 2. One metropolitan city and two small cities were selected to compare the difference between residents' opinion in each area and to find out how the characteristics of each city would be reflected to it. In case of Gangseo District in Seoul representing highly dense area, the rate of population connected to public sewerage is 100 % and the population density is over 19,000 capita/km^2. In case of Dangjin, coastal city and Jincheon, interior city, the population density and the rate of population connected to public sewerage are relatively low, which may be the typical trait of small cities in Korea.

Table 2 Population, areas, and public sewerage connection rates in research areas

Area	Population	Households	Area (km^2)	Connected to public sewerage (%)	Size
Gangseo	543,559	193,629	41.4	100.0	Metropolitan city
Dangjin	135,106	52,151	664.7	59.5	Small city (coastal area)
Jincheon	59,324	22,603	405.9	65.3	Small city (inland area)

The least number of samples for analysis was estimated before the survey was performed. In general, "10 samples per predictor" was proposed by [9] as a criterion in partial least square (PLS) analysis. To determine the number of predictors, the largest number of predictors was chosen for the number of predictors with identification of paths (arrows) toward each latent variable. However, recent researches pointed out that there would be problems in verification capability when the number of required samples was determined by this criteria. Several researchers [10, 11] proposed to determine the number of minimum samples through statistical power analysis.

In this study, the number of minimum samples was determined using a computer software (G*Power 3.1) with the verification capability to predict the minimum number of required samples. In the CSI model as shown in Fig. 1, the three predictors (flooding, clogging, odor) of sewer service quality were adopted and the minimum number "119" of the required samples was obtained by G*Power analysis. Therefore, 366 samples from questionnaire (120 samples in Gangseo, 120 samples in Dangjin and 126 samples in Jincheon) were collected in this study.

4 Results

The reliability of the measured variables was tested by assessing the consistency of the variables using Cronbach's α test. A Cronbach's α of 0.6 or higher is generally considered an acceptable level of reliability. Cronbach's α of the measured variables was estimated to be 0.68 or greater for all variables (threshold = 0.6). This suggests a satisfactory level of consistency.

Next, measured variables were tested for factorial validity and discriminant validity. To test the factorial validity of the variables, a confirmatory factor analysis (CFA) was performed, and to test the discriminant validity, their average variance extracted values were estimated using AMOS 20. The CFA, which was performed to test the factorial validity of the measured variables, resulted in factor loadings of 0.6 and higher, which is well above the recommended value of 0.5, except for the willingness to accept the increase sewerage fee. Thus, we proposed the simpler secondary CSI model, as shown in Fig. 2. Hypotheses 3 and 4 proposed as shown in Fig. 1 and in Sect. 2 were ruled out in the secondary CSI model (Table 3).

As described in Fig. 2, the primarily proposed CSI model was restructured into revised CSI model based on the hypotheses that customer satisfaction would relate to two latent variables, sewer service quality and clean environment. These three latent variables could be estimated by seven measurement variables. Table 4 shows the result of goodness of fit of the revised CSI model. In general, the root mean square error of approximation (RMSEA) is known to be good below 0.05 and is acceptable between 0.05 and 0.8 [12]. In case of TLI (Turker-Lewis index) and CFI (Comparative fit index), it is known that they are good when greater than 0.9 [13, 14]. As one can see in Table 4, the model meets the criteria of TLI and CFI quite well but RMSEA. Though goodness of fit of the revised CSI model needs to be investigated

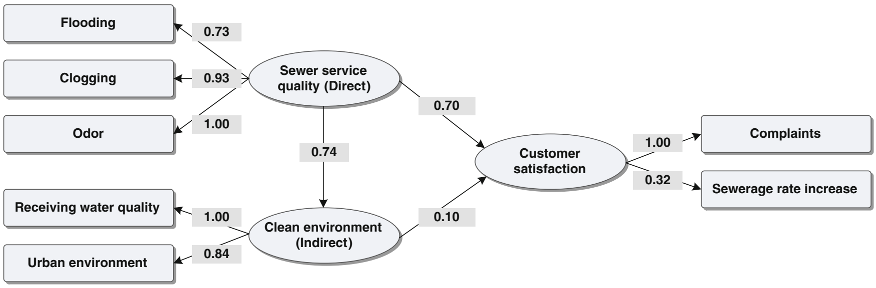

Fig. 2 Results of revised customer satisfaction index model with path coefficients for all three research sites (All measurement and path coefficients are significant at $p < 0.05$)

Table 3 Results of confirmatory factor analysis for the primary proposed CSI model

Measurement variables	Latent variables		
	Sewer service quality	Clean environment	Customer satisfaction
Flooding	0.813		
Clogging	0.832		
Odor	0.735		
Receiving water quality		0.642	
Urban environment		0.596	
Complaints			0.702
WTA increased fee[a]			0.219

[a] WTA means willingness to accept

Table 4 Goodness of fit test for research model

x^2	Degree of freedom	Comparative fit index	Turker-Lewis index	Root mean square error of approximation
26.715	11	0.951	0.974	0.063 (0.033–0.093)

( ) confidence interval

further, the result of CSI model proposed as the initial phase of this approach is worthwhile to discuss the causal relationship of quality factors for customers with wastewater service.

The results of testing the model and its hypotheses were given in Fig. 2. All hypotheses were accepted with exception of Hypotheses 3 and 4 suggested in Sect. 2. Figure 2 was depicted with exclusion of Hypotheses 3 and 4. Based on these results, the quality factors to affect customer satisfaction with wastewater service were sewer service quality and clean environment quality. The higher quality of both sewer service and environment could increase customer satisfaction.

The effect of sewer service quality on the customer satisfaction was much greater than that of environment quality (0.70 vs. 0.10). The effect of sewer service quality on environment improvement appeared to be very important since its path coefficient was 0.74. Though the sewer service quality seemed to directly improve environment quality (0.74), however, it is noticeable that the environment quality improved through sewer serve quality did not increase the customer satisfaction (0.10).

Even though the sewer flooding was expected as more serious quality factor than sewer blocking and odors, which could cause damage to public or private properties and human heath, customers seemed more interested in their neighboring inconvenience. From customers' viewpoints, sewer odor problem was very important factor, suggesting that public officials and partners related to sewerage works should keep it in their minds. Customers were not willing to accept the increased sewerage fees even if both sewer service and environment quality surely contributed to improve their satisfaction. On the other hand, the higher the customer satisfaction would be, the lower the number of complaints could be.

We intended to compare the difference of customer recognition and satisfaction with wastewater service among three cities. The path coefficients of the revised CSI model at three cities were shown in Table 5. Residents in Seoul and Dangjin were more interested in sewer odor problem than those in Jincheon. In fact, some parts of Jincheon on July, 2011, 2 months before the survey, experienced severe drainage problem on account of the heavy storm water, resulting in significant damage to their farming and other properties. This fact seemed to affect the survey and then make a little different trend of path coefficient values in Jincheon from those in other cities.

Table 5 Comparison of path coefficients of the revised CSI model applying to three cities

Path between latent variables	Gangseo	Dangjin	Jincheon	Overall
Flooding → Sewer service quality	0.71	0.65	0.90	0.73
Clogging → Sewer service quality	0.70	0.95	1.11	0.93
Odor → Sewer service quality	1.00	1.00	1.00	1.00
Receiving water quality → Clean environment	1.00	1.00	1.00	1.00
Urban environment → Clean environment	0.61	1.04	0.75	0.84
Sewer service quality → Clean environment	0.80	0.66	0.91	0.74
Sewer serve quality → Customer satisfaction	0.49	0.48	1.08	0.70
Urban environment → Customer satisfaction	**0.12**	**0.32**	**−0.25**	**0.10**
Customer's satisfaction → Complaints	1.00	1.00	1.00	1.00
Customer's satisfaction → Sewerage rate increase	**0.18**	**0.53**	**0.20**	**0.32**

5 Conclusions

In this study, the customer values and concerns on sewer service in three places in Korea were surveyed and the customer satisfaction index model was proposed to see cause and effect relations of principal parameters influencing the sewer service level. In the revised CSI model, sewerage service quality and improvement of environment affect customers' satisfaction. In case of the sewer service quality, odor and clogging are relatively more important than flooding, meaning end-users are more interested in their neighboring environmental concerns and inconvenience. The effect of sewerage service quality on surrounding environment is significant, while the effect of environmental improvement on customer satisfaction is relatively small. Customers do not seem to have the willingness to accept the increased sewerage fee even if the sewerage quality and environment are surely improved from the current state. This approach can be expected to stimulate the development of similar but better approaches as tools for promoting the understanding of the essential customers' value.

Acknowledgments This research was supported by the Chung-Ang University Research Scholarship Grants in 2007.

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Lean Approaches in Asset Management Within the Mining Industry

Jared Ross Flynn and P.J. Vlok

Abstract Companies such as Toyota have been successful in implementing approaches of Lean Thinking (such as Kanban, Kaizen and 5S) to eliminate non-value adding processes. Mining companies often experience a lot of waste generated from non-value adding processes and often do not minimize the waste proactively. This waste includes physical material waste extracted from processes, idle time during processes, defects in products, excess inventory (including keeping too many spare parts on hand) and overproduction. This waste results in a lack of productivity, inefficiencies, pollution, overuse of available resources and a lack of quality in products or services. This paper discusses the modern Lean Thinking approaches that have been applied successfully within the automotive industry, as well as within non-manufacturing industries such as the post office industry and health care industry. Their current application within the mining industry is also investigated. Case studies of three mining companies that have adopted Lean Thinking successfully, Rio Tinto, PT Inco and a Votorantim Group fluorspar mine, are discussed and the benefits of Lean Thinking to such mining companies are provided.

1 Introduction

Traditionally, businesses have been focused on generating larger profits, increasing efficiency and improving quality. However, in today's global and highly competitive economy, these objectives have become of greater strategic importance and companies are striving towards greater agility while using existing or even fewer

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_9

resources. Currently, manufacturing industries such as the automotive industry and electronics/computer industry have been at the forefront of implementing innovative approaches to remain competitive while the mining industry has less incentive to implement such strategies. Lean Thinking is one such approach used within industries to improve performance, especially in highly competitive environments.

The principles of Lean Thinking can be traced back to 1913 when Henry Ford focused on processes within Ford Motor Company and introduced conveyor-belt assembly lines. Many Lean Thinking principles were conceptualized in his book, *Today and Tomorrow*, written in 1926. However, the theory was only truly formalized as an approach by the Japanese automotive giant, Toyota, and described in *The Toyota Way* by Jeffrey Liker nearly 80 years later.

Certain industries have been successful in applying Lean Thinking. The company that made Lean Thinking a way of life, Toyota, developed The Toyota Production System (TPS) in response to the restricted environment in which it operated in order to survive. Unlike Ford Motor Company with its mass production of the same model of automobile, Toyota was required to produce a small quantity of a variety of automobile models. Resources were limited, demand much less and mass production was not possible in the same way in which Ford Motor Company had implemented it in America [22].

Many of the modern industrial approaches applied in industry have similar objectives. Six Sigma is concerned with improving quality by decreasing variability in processes which correlates to the Lean Thinking of avoiding poor quality or defects (a form of waste). Total Productive Maintenance (TPM) focuses on mistake-proofing to reduce incidents such as defects and accidents. A Lean organization ideally uses a variety of these approaches to eliminate waste and increase the value of their processes.

Lean Thinking originated from the manufacturing industry and has proven to be successful in industries of the same nature as such an industry. There is some scepticism, however, as to whether Lean Thinking can be applied to industries of a nature different to the manufacturing industry. The mining industry is a dynamic environment containing dust and harmful outdoor conditions. It is not the clean, stable, contained environment of a manufacturing plant. However, according to [22] (pp. 7–8), “the principles of lean production can be applied equally in every industry across the globe and the conversion to lean production will have a profound effect on human society.”

This paper discusses the modern Lean Thinking approaches that have been applied successfully within the automotive industry, as well as within non-manufacturing industries such as the post office industry and health care industry. Lean Thinking within the ISO 55000 [1] framework is also considered and the current application of Lean approaches in the asset management environment within the mining industry is investigated. Case studies of three mining companies that have adopted Lean Thinking successfully, Rio Tinto, PT Inco and a Votorantim Group fluorspar mine, are discussed and the benefits of Lean Thinking to such mining companies are also provided.

2 Types of Waste in Lean Thinking

According to [3], "Lean is the ceaseless elimination of waste." In Ref. [16] the authors define seven types of waste which Lean Thinking aims to reduce:

i. Overproduction—producing items for which there are no orders.
ii. Waiting or idle time—resources idling due to no work or having to wait for other parts of the process.
iii. Incorrect processing—using more steps than is necessary to complete process.
iv. Unnecessary motion—any motion performed such as walking, looking, reaching or stacking parts.
v. Transportation or conveyance—carrying Work-In-Process (WIP) long distances or moving materials, parts or finished goods into or out of storage between processes.
vi. Excess inventory—Excess raw materials, WIP or finished goods increasing storage costs, transport costs, risk of damage and length of lead times.
vii. Defects—any time, costs, effort and lack of quality as a result of production of defective parts or correction of those parts.

Examples of these types of waste within asset management include spare parts as excess inventory, idling of machines or the failure of assets due to defects. These forms of waste result in a lack of productivity, inefficiencies, pollution, overuse of available resources and a lack of quality in products or services. Various approaches are implemented within a Lean organization to reduce these forms of waste.

3 Modern Lean Thinking Approaches

Reference [3] further state that Lean Thinking, in practice, relies on the application of a suite of business improvement tools in combination with engaged workplace leaders and empowered employees. Employees at the lowest level in the organization should be given the responsibility to make operational decisions, as well as to formulate their own standards and continuously improve them. This is in contrast to traditional "non-lean" organizations in which managers in higher levels are responsible for almost all of the operational decisions. The manager's role in a lean organization is to provide resources, to challenge employees to continually improve and to coach employees to develop problem-solving skills.

Lean Thinking includes numerous Lean principles and tools aimed at reducing waste in all its forms, but the majority of principles and tools depend on the Foundation Elements (groundwork of Lean Thinking). The Foundation Elements consist of TPM and Quick Changeover (QCO), 5S and Visual Factory, and Standardized Work [3]. Therefore, a Lean organization should focus first on Foundation Elements before implementing principles such as Takt Time and Jidoka.

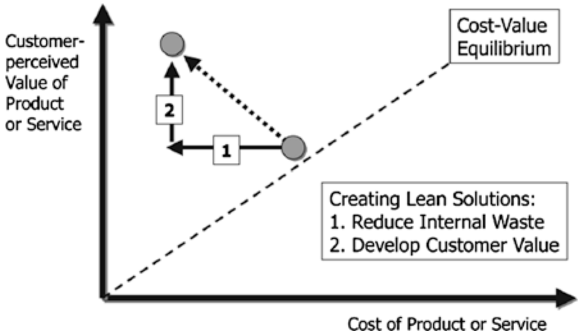

Fig. 1 Relation of value, cost and waste in Lean Thinking [6]

Kanban, Kaizen, Six Sigma and Just-In-Time (JIT), among other approaches or techniques, are popular for their use in reducing waste within organizations. The waste is reduced often to reduce the cost of the product which allows the organization to either reduce the price of their products or, the preferred approach, to reallocate the funds saved to increase the value of the products.

Figure 1 illustrates the value-versus-cost relationship followed within Lean Thinking. The cost-value equilibrium indicates the positions where the value (the perceived worth for which the customer is willing to pay) of the products or services exactly equals the costs of the products or services. A product or service which is higher above the cost-value equilibrium is more attractive to customers while positions below the cost-value equilibrium are undesirable. Lean Thinking aims both to reduce cost and to create value by first reducing the cost of products or services and then increasing value, focusing on retaining only value-adding processes.

3.1 5S and Visual Factory

The 5S and Visual Factory Foundation Element is concerned with tidiness, organization and accessibility of workplaces and processes. According to [7], 5S is the name given to the following five important housekeeping steps (with the Japanese coined terms in parenthesis): sort (seiri), straighten or set in order (seiton), scrub or shine (seiso), standardize (seiketsu), and sustain (shitsuke).

5S is essentially about organizing the workplace in an organized manner such that tools and equipment are located as close as possible to where they are required without becoming obstructions. Shadow boards (boards on which tools hang with the shapes of the tools painted onto the board where they should hang) aid with this by allowing for easy visual inspection of what tools are currently either missing or being used. Furthermore, only the designated tools and equipment are used in the workplace resulting in much less confusion, dust and ash.

3.2 Standardization

Standardization is implemented by first assessing existing practices for processes and then documenting baseline procedures for the processes. Procedures are incrementally improved through suggestions from employees or by implementing trial and error approaches. The baseline procedures, which are implemented throughout the organization, make the processes measurable and provide a means of comparison when implementing new procedures [3].

Standardization is a core principle within Kaizen methodology. According to [10], best practice is assured with standardized work and current best practice becomes the baseline for further improvement. Indeed, [8] state that standardized work prescribes the procedures such that they result in minimum human effort, maximum safety, zero defects, minimum time and minimum waste. Most importantly, standards provide a means of measuring performance.

3.3 Total Productive Maintenance (TPM)

Total Productive Maintenance (TPM) is a maintenance strategy where strong focus is placed on taking proper care of equipment. Maintainers and operational employees are brought together to figure out how to improve the Overall Equipment Effectiveness (OEE). OEE is a measure that indicates the percentage of planned production time that is truly productive. According to [15], OEE is calculated from Eq. (1),

$$OEE = A \times P \times Q \tag{1}$$

where A is the percentage of availability (ratio of operating time over scheduled production time), P is the percentage of performance (ratio of theoretical production time over operating time) and Q is the percentage of quality (ratio of good units over total production units).

Reference [8] describes TPM as being an extension of Preventative Maintenance (PM) where equipment is maintained to ensure a perfect working state when it is scheduled for production. This is achieved by operators performing routine maintenance known as autonomous maintenance and maintainers performing scheduled maintenance to ensure that equipment remains operational. Employees are expected to metaphorically take ownership of equipment, to understand the relationship between operation and wear and tear, to contribute suggestions for improvement and to perform routine checks to ensure equipment is in proper condition before using it [8]. Ideally, equipment is returned to its original state and sources of excessive wear are eliminated as far as possible.

3.4 Quick Changeover (QCO)

Quick Changeover (QCO) refers to the capability of maintenance or an operational change to occur with minimal impact on production. All elements required during a changeover for maintenance or an operational change are identified and then classified according to external tasks or internal tasks. External tasks are elements that can be performed without production equipment ceasing. Internal tasks are elements that cannot be performed without the production equipment being stopped. The production downtime is reduced by converting as many internal tasks as possible to external tasks [3].

3.5 Value Stream Management (VSM)

Value Stream Management (VSM) is a strategic and operational approach which aids a company in achieving Lean status. Reference [18] describe the process in the following steps:

i. Commit to lean
ii. Choose the value stream
iii. Learn about lean
iv. Map the current state
v. Determine lean metrics
vi. Map the future state
vii. Create Kaizen plans
viii. Implement Kaizen plans.

According to [18], it has been successfully used to implement lean manufacturing in Fortune 500 companies. Furthermore, according to [19], VMS was the most important and most overarching Lean tool of the successful tools implemented in the study which he performed. However, he also states that VMS has drawbacks such as hesitancy of employees to implement recommendations and the difficulty in evaluating a future state map due to its static nature.

3.6 Kaizen

Kaizen is a Japanese word which describes continuous incremental improvement [21]. Kaizen is not focused on revolutionary innovation (although such innovation is allowed using the Kaizen approach), but rather ideas are sought for small problems or improvements on a daily basis. According to [12] (p. 178), “these small ideas tend to remain proprietary, accumulating over time into sustainable competitive advantage.”

A Kaizen approach requires ideas and input from the lowest level in the organization (the people actually doing the work) since managers often only see a fraction of problems present. According to [7], the major focus of Kaizen must be housekeeping, waste (known as muda) elimination and standardization. He states that "introducing good housekeeping in the *gemba* (actual workplace or shop floor) reduces the failure rate by 50 %, and standardization further reduces the failure rate by 50 % of the new figure." The organization also becomes more process-focused and less results-focused, following the belief that the right results will be obtained when the right processes are in place.

Kaizen ultimately assures attention to detail, involvement of all employees to improve the organization and a culture which is flexible, responsive and adaptive that makes change and improvement commonplace. Kaizen is also low-risk, inexpensive, subtle and undramatic [7].

3.7 Lean Six Sigma

Six Sigma is a statistical term which defines the quality of a process or product as having less than 3.4 defects per million. The Six Sigma process uses two methodologies, namely DMAIC (Define, Measure, Analyse, Improve and Control) to improve an existing process and DMADV (Define, Measure, Analyse, Design and Verify) to implement a new process or service [2].

Although not necessarily a Lean principle, Six Sigma is often used in Lean Systems to reduce process variation. This is then referred to as Lean Six Sigma which is a combination of Lean Thinking and Six Sigma that results in both the elimination of the seven types of waste and processes involving only 3.4 defects per million opportunities.

3.8 Other Lean Approaches

Just-In-Time (JIT) is a philosophy intended to smooth the manufacturing process by "providing the right materials in the correct quantity and quality, just in time for production to eliminate or reduce waste, thus producing the maximum value for the customer" [13]. *Andon* involves visual display boards to provide visual feedback to the workshop. *Poka-Yoke* is simply "mistake-proofing" where all potential sources of mistakes are identified and eliminated. *Jidoka* is defined as "automation with a human touch" [20]. *Root Cause Analysis (RCA)* involves identification of possible causes for problems and, instead of dealing only with the symptoms of any problems, the actual sources of problems are eliminated. *Toyota Production System (TPS)* is a system in which any improvement is implemented according to a scientific method at the lowest level in the organization and under the guidance of a mentor [5].

4 Lean Thinking Within ISO 55000 Framework

Lean Thinking is a continuous improvement strategy which is in line with ISO 55000 asset management. According to ISO 55000, "asset management does not focus on the asset itself, but on the value that the asset can provide to the organization."

The standard considers asset management to be based on a set of four fundamentals, namely: value, alignment, leadership and assurance. Lean Thinking is concerned with reduction of waste and, ultimately, the increase of value. TPM, for instance, is focused on operator care with regard to operators maintaining equipment in a condition either as good as or better than what it originally was. This is a form of asset management where assets are managed to bring value to the organization and its stakeholders as described by ISO 55000.

Lean Thinking is strongly dependent on leadership and workplace culture. All employees are encouraged to 'own' the equipment which they use and the ideas which they offer to the workplace. Furthermore, motivation and behaviour can also have a significant influence on the achievement of asset management objectives.

Certain principles of Lean Thinking also aim to improve the performance and reliability of assets, such as TPM and VSM. This provides assurance that assets will fulfil their required purpose which is a requirement of asset management. Assurance according to ISO 55000 entails implementing processes for monitoring and continual improvement which Lean Thinking requires as well.

Many of the Lean principles are incorporated well within asset management as defined by ISO 55000. Figure 2 illustrates the domains in which the ISO 55000 asset management system and Lean Thinking apply.

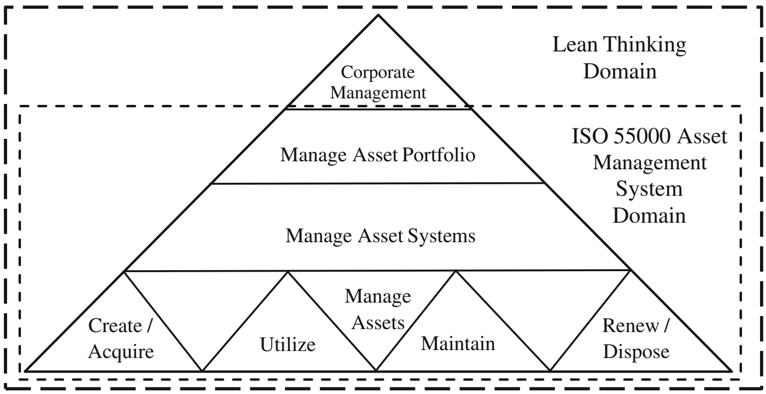

Fig. 2 Link between Lean Thinking and ISO 55000 asset management (adapted from [4])

5 Successful Implementation in Industries Other Than Mining

Lean Thinking has been applied to different types of industries with varying success. Two industries which have been very successful at adopting Lean Thinking, other than the manufacturing industry, are described in this section.

5.1 *Post Office Industry*

The post office industry is a service industry that requires high efficiency and little clutter. Processes within this industry are easily standardized and streamlined. Lean Thinking, therefore, is often successful in such an industry due to the continuous processes required.

The Canada Post Calgary Plant is an example of the potential applicability of Lean Thinking to industries other than manufacturing industries. The organization recognized signs of waste from the mail being transferred in large batches from one sorting area to another with long waiting times in between changeover times. The team first defined what value meant for their customers. Then they performed Value Stream Mapping to help them determine where they should focus. They assessed the flow of mail through the processes and removed bottlenecks by reducing changeover times on the large sorting machines. The company determined what tasks were waste such as picking up and putting down bags more than necessary. Finally, they eliminated wasteful processes and determined a Takt Time of 24 s/bag [14]. The Canada Post Plant managed to achieve the results tabulated in Table 1.

5.2 *Health Care Industry*

The health care industry is not an industry in which a person would intuitively see the application of Lean Thinking. It is also an industry which is very different in nature to the manufacturing industry, especially since time by a medical professional is one of the commodities instead of products such as vehicles. However,

Table 1 Results achieved by canada post calgary plant using lean thinking [14]

Results	Before lean	After lean
Space used	17,000 sq. ft.	9,500 sq. ft.
Number of operators	10–15	6–7
Productivity	19 bags/hr	25 bags/hr
Lead time	2.03 days	0.98 days
Bag travel distance	2,294 ft.	1,580 ft.

some health care institutions have been highly successful in applying the Lean principles to their organizations.

The Mayo Clinic in Rochester, Minnesota, is, according to [17], one of the most prestigious healthcare institutions in America and has been named by *Fortune* magazine as one of the 100 best companies for which to work in America. Furthermore, for at least 16 consecutive years, *U.S. News & World Report* named Mayo Clinic one of America's best hospitals. Despite the institution's great success, it still strives for improvement and has implemented Lean Thinking into its structure.

The Mayo Clinic's cardiovascular division had no pressure to change how it was operating, but Dr. David Hayes (Chair of the Division of Cardiovascular Diseases) believed that the institution could do better and initiated the incorporation of Lean principles into the division. The Cardiovascular Health Clinic (CVHC) was identified as the target for lean since it was experiencing "problems with no-shows, cancellations, perceived lack of demand and dissatisfaction among both allied staff and physicians with the efficiency of the entire patient journey" [17]. One important problem was that patients were often asked for the same information numerous times by different people.

The Mayo Clinic used Lean Thinking to eliminate steps that were not necessary and then implemented Six Sigma to perfect each step of the process and minimize variation. Standardization played a very important role at the clinic.

Reference [17] reports that cancellations and no-shows at the Mayo Clinic declined from 30 to 10 % following the initial implementation of Lean Thinking. The number of high-yield patients increased from 150 to 200 per month and physician fill rates increased from 70 to 92 % which meant that the Mayo Clinic was utilizing resources more efficiently. The number of steps in the entire patient process decreased from 16 to 6 while the face time that patients had with doctors increased from 240 to 285 min. There was also a 91 % reduction in the wait time (the time between the request for an appointment to finishing the pre-care consultation).

6 Case Studies of Lean Thinking in Asset Management Within the Mining Industry

The dynamic nature of the mining environment creates a high degree of uncertainty in various unit operations [20]. This makes the applicability of Lean Thinking to the mining industry difficult. Table 2 tabulates the differences between a resource or minerals organization and an automotive organization as reported by [3]. These differences can increase the difficulty of applying Lean Thinking to the mining industry since the environment is completely different to the manufacturing industry (from where Lean Thinking was derived).

Table 2 Comparison between resource/minerals business and automotive business (Ref. [6])

Resource/minerals business	Automotive business
A smelter or refinery cannot be stopped so there is inherent production push in the process	An automotive assembly line can be stopped so there is the ability to create pull systems
Production is in continuous units and around the clock	Production is in discrete units and often on less than 1 day cycles
Generates considerable dust	Little dust generated
Physically challenging environment	Ambient conditions
Inherently variable environment	Stable work environment
Remote locations	Large centres
Impact of weather	Indoor environment
Inherently variable raw materials	Controlled raw materials
Geographically spread output teams	Compact plants
Molten metal has a short shelf life before it solidifies	Long-life components suitable for supermarket-style storage

Despite the differences between the mining industry and the automotive industry, both industries share common views in [20]:

i. Safety
ii. Effective business processes
iii. Efficiency within the Value Stream
iv. Maximizing operational efficiency
v. Operating within extensive supply chain.

According to [11], the primary reason companies fail when applying Lean principles or tools is due to a lack of understanding the underlying concepts which makes them work well together in a system. Lean Thinking is not merely a tool used to improve company performance and profitability, but is rather a culture or mindset of continuous improvement which needs to be understood and applied in its entirety. A few case studies of where Lean Thinking has been applied successfully within the mining industry are discussed in this section.

6.1 Rio Tinto

Rio Tinto is one of the best examples of the application of Lean Thinking within the mining industry. They have applied Lean Thinking to many of their operations and mining sites, primarily in Australia, and the results have been very successful for them. Rio Tinto Aluminium (RTA) was the first group within Rio Tinto to introduce Lean Thinking in 2004 with the assistance of UK-based consultant Lean Manufacturing Resources (LMR). RTA already had a Six Sigma improvement program in place and planned to use Lean Manufacturing to achieve continuous improvement activities at a workplace level. According to [3], “Lean has achieved good and sometimes spectacular results improving productivity and efficiency at all sites, including the mining site”. It also improved Rio Tinto Aluminium’s ability to develop and retain employees [3].

A$25 million worth of improvements has been achieved by Rio Tinto Aluminium each year from Six Sigma projects since 2003 [3]. Six Sigma has played an important role within RTA, especially by creating a data-based, problem-solving atmosphere which made the adoption of Lean Thinking principles even easier. Focus began to change from corrective measures (correcting errors or solving problems which have occurred) to pre-emptive measures (anticipating potential problems and identifying improvement opportunities).

The first application of Lean Thinking in RTA was at the Carbon Bake Furnace at Boyne Smelters. Traditionally, daily production meetings were held in parallel to manufacturing meetings to discuss current progress of operations. However, when a new Information Centre (IC) was set up, the production meetings became redundant. The IC provided a real-time view of production performance on the walls of the IC and the brief daily manufacturing meetings allowed operators, maintainers and contractors to cooperate in solving problems and addressing any issues that arose. Within 6 months, previously unsolvable issues had been quietly resolved and the Carbon Bake Furnace was ahead of schedule for the first time [3]. The Information Centres focused on six metrics to gauge the progress of production to align to the six pillars of RTA’s corporate strategic map. The six pillars are:

i. Health and safety
ii. People commitment
iii. Environment and communities
iv. Market position
v. Operational excellence
vi. Financial strength.

According to [19], performance metrics are necessary in determining the success or lack thereof of Lean Thinking efforts. The metrics were displayed either on a graph or on a green cross (a diagram illustrating each shift of each day of the month with a corresponding colour representing a setback, a status quo or an improvement). The ICs were also located centrally so that everyone has access to them. This allowed all levels of the organization to be aware of production performance and encouraged a greater sense of responsibility and control over processes.

In terms of housekeeping (5S), the Carbon Bake Furnace used shadow boards to ensure that everything has a well-defined place. They also used single point lessons which are A4 pages in a standardized format that indicate the proper operation of equipment to which they are attached. Kamishibai boards (boards with double-sided cards) were used to indicate whether scheduled tasks had been performed [3]. Table 3 displays the results obtained by the Carbon Bake Furnace between 2004 and 2006, after implementing Lean Thinking.

Rio Tinto’s Weipa mine in Queensland, Australia, implemented Lean Thinking by using a resident external consultant and carefully trained coaches within the

Table 3 Results achieved by Carbon bake furnace between 2004 and 2006 [3]

Results	2004	2006
Health and safety		
Incidents	154	67
First aid	24	0
Lost work days	1	0
Medical treatment	1	0
People commitment		
Turnover	15.5 %	9 %
Absenteeism	3.4 %	1.8 %
Environment and communities		
Odours	14	2
Market position		
Conformance to heating curve	70 %	88 %
Anode rejects	2 %	0.9 %
Operational excellence		
Carbon dust	20 %	6 %
Net carbon ratio	0.431	0.410

organization. Information Centres were set up for all business areas to enable employees and managers to see how the teams were performing. The consultant and coaches encouraged employees to take ownership of their own improvement initiatives [5]. The project's success was largely attributed to training of all employees and using vertical analysis of the organization instead of a horizontal analysis to ensure that employees at workshop level are included within the management improvement strategy. Employees are now more willing to identify and solve problems affecting production. Furthermore, operational and maintenance teams share a common purpose and sense of ownership and have become united through the Lean Thinking process [5].

The organization extended the approaches to Northparkes Mines, a copper mining operation in Central New South Wales, and Hunter Valley Operations, a group of four coal mines in New South Wales. Dunstan, Lavin and Sanford (2006) report that the Lean Information Centres at Northparkes have contributed to a 56 % improvement in the production cycle times within the first 30 days of adoption. Lean Thinking was then also adopted by Rio Tinto Iron Ore.

6.2 *PT Inco's Sulawesi Island Mine*

The Sulawesi Island Mine of PT Inco (currently named PT Vale) in Indonesia reported significant initial efficiency gains as a result of a project using Lean Thinking, but emphasized the critical importance of an employee engagement programme. According to [5], such a programme should facilitate in achieving more in the short-term, as well as sustaining gains in the longer term. The PT Inco Mine initially operated in silos where operating teams never communicated with each other. As a result, impediments to performance were not discussed constructively. However, the company was able to engage employees, through training and coaching, by ensuring that every employee understood how their own individual contribution helped to achieve the overall business goals, as well as the role it played within their team and department [5].

6.3 Votorantim Group Fluorspar Mine

A study was performed in a fluorspar mining company of Votorantim Group in Santa Catarina State, Brazil, where the mapping of the production process was carried out using TPS concepts and techniques. The operations performed before Lean Thinking in the mining block analysed are illustrated in Fig. 3.

According to [9], drilling and blasting (together forming 45 %) are considered to be essential operations. Preparation (14 %) involves connecting compressed-air hoses, among other activities, and is considered to be an auxiliary operation. Sharpening drills (<1 %), changing clothes (2 %), commuting (10 %) and lunch time (5 %) are also considered to be auxiliary operations. The resting time (8 %) is an auxiliary operation since it relieves miner's fatigue, but is not directly critical to performing the primary operation. Wasteful operations include waiting (14 %) and ventilation (1 %) which form 15 % of operational time performed. Lean Thinking was implemented to identify the sources of waste. It was found that the essential drilling and blasting operations were performed individually by the same driller who was responsible for sharpening drills and retrieving the explosives. This generated idle time of the drilling machine while the driller was performing the auxiliary tasks.

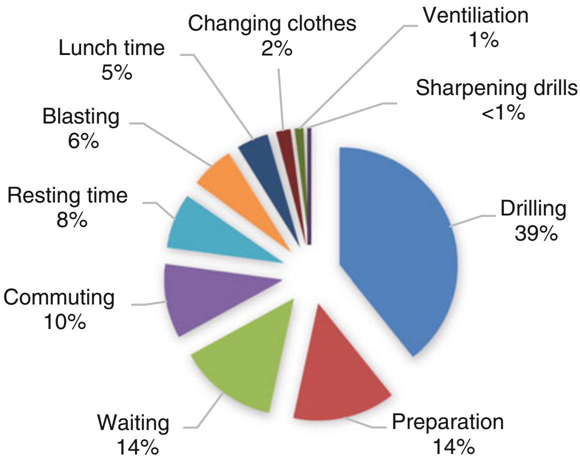

Fig. 3 Pre-Lean operations performed in mining block at fluorspar mine [9]

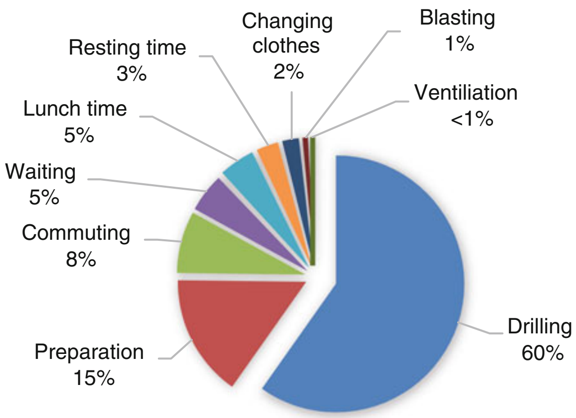

Fig. 4 Post-Lean operations performed in mining block at fluorspar mine [9]

The solution was to have a team of three drillers alternating operations. While two were drilling, the third member would perform auxiliary operations. The sharpening of drills operation was reallocated to an external worker.

Valves were also positioned too far away from the drilling machine, causing drillers to have to travel relatively long distances to open and shut the valves (waste in the form of motion). Positioning valves closer resulted in less idle time and less fatigue of drillers. Ventilation was also improved to reduce the time required for ventilation at certain times.

Figure 4 illustrates the percentage each operation consumes of operational time after Lean Thinking was applied to the mining block. Drilling increased from 39 to 60 % while total wasteful operations (waiting time and ventilation) decreased from 15 to 6 % [9].

Reference [9] report that the mining block extracted a volume of ore of 15.72 tons/driller before the implementation of the Lean Thinking process.

After implementation of Lean principles, the mining block extracted 22.58 tons/driller which resulted in a gradual increase in the monthly volume extracted inside the block increasing from 5,661 tons to 8,129 tons (43.6 % higher yield). The cost per ton extracted within the mining block decreased by 32.9 % from US$5.23/ton to US$3.51/ton [9].

7 Potential Future of Lean Thinking Within Mining

To be successful in applying Lean Thinking to mining industries, the concerned organizations need to consider the entire mining chain and not just a plant within the organization. Ideally, suppliers and customers are included completely into the analysis for Lean Thinking. Therefore, the mining organization will consider the chain from mine exploration to mine reclamation, including, among others, mine planning, mine drilling, smelter operations, transportation and distribution [20].

Reference [9] state that the technological knowledge of "mining and processing methods is not enough to ensure the survival of mining organizations." They reason that it is also necessary for management methods to be aligned towards competitiveness with mines focusing on the reduction of production costs and the increase in profits [9], and [5] state that efficient and effective operations will define a mine's competitive edge as mining methods mature and stabilize. This implies that wasteful processes that have been allowable by mining companies in the past, may not be sustainable in the future and mining companies are advised to incorporate Lean principles into their business strategies.

According to Russell Sanford, who is Rio Tinto's Improving Performance Together (IPT) Team Leader, as cited in [3], "Lean is as effective in a mining environment as in a manufacturing one." Despite initial resistance based on the belief that the mining industry is completely different to the automotive industry, there has been rapid acceptance that Lean Thinking adds value and is consistent with the basic mining processes. Barry Lavin, Managing Director of Northparkes Mines, considers mining to be a vastly different environment to manufacturing, but believes it is similar in that the development process is sequential with each step in the process to be completed before the next step is undertaken [3].

Lastly, [8] state that there is significant value in implementing an organization-wide strategy, but to be successful the intervention requires leadership from senior management, involvement from all levels, high investment in training and the use of change agents. Such a strategy also takes a considerable amount of time to implement.

8 Conclusion

As companies mature, they require a more competitive edge to survive and/or thrive. The technological knowledge they possess eventually becomes insufficient in ensuring survival. Lean Thinking is a strategy which provides companies, including mining companies, a competitive edge by eliminating waste and increasing value to the organizations. Lean Thinking uses many approaches such as Kanban, Kaizen, 5S, Standardization, TPM and VSM to achieve this increase in value. Ultimately, these approaches aim to increase value by reducing seven types of waste, namely overproduction, incorrect processing, waiting or idle time, unnecessary motion, transportation, excess inventory and defects.

Lean Thinking has been very successful in the manufacturing industry from which it originated, but it also has been successfully implemented within other industries, such as the healthcare industry and the post office industry. Case studies of the Canada Post Calgary Plant and Mayo Clinic illustrate the possible success of Lean Thinking within non-manufacturing environments. The Canada Post Calgary Plant managed to nearly half space used, number of operators and lead times, as well as increase productivity by more than 30 %. The Mayo Clinic, on the other hand, increased high-yield patients per month from 150 to 200 and achieved a 91 % reduction in wait times.

There has been disagreement over whether Lean Thinking can be successfully implemented within the mining industry due to the completely different environment relative to the manufacturing industry. However, Lean Thinking has been successful in the mining industry at mining companies such as Rio Tinto, PT Inco and Votorantim Group. Rio Tinto Aluminium's Carbon Bake Furnace achieved more than half reductions in safety incidents, odours, anode rejects and carbon dust between 2004 and 2006. The Votorantim Group fluorspar mine managed to increase monthly volume extracted inside the mining block by 43.6 % while decreasing the cost per ton extracted by 32.9 %.

An important point is that Lean Thinking requires, in order to be successfully implemented, an organization-wide approach at all levels with all employees being engaged into the programme.

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Integrating Tacit Knowledge for Condition Assessment of Continuous Mining Machines

Joe Amadi-Echendu and Marc de Smidt

Abstract Conventional condition monitoring places emphasis on selective measurements and analyses of physical parameters like acoustic noise, vibration, pressure and temperature but, this approach can be suboptimal in providing sufficient information for assessing the condition of an engineering asset. Starting from the definition of reliability, an exploratory investigation was conducted into how to integrate tacit experiential knowledge to assess the condition of continuous mining machines. Semi-structured interviews were conducted with engineers representing five different mine shafts involving more than 30 continuous mining machines. The respondents reiterate that experience of the specific operational environment improves the credibility of data and information derived from conventional condition monitoring of the physical parameters, reinforcing the view that tacit experiential knowledge is invaluable to assessment of the condition of engineering assets.

Keywords Condition assessment · Continuous mining machines · Reliability

1 Introduction

Mining firms and machine manufacturers are always concerned about improving the value provided by continuous mining machines (CMM) deployed in underground operations [22, 23]. Typically, the focus tends to be on narrow short term measures aimed towards reducing maintenance costs, even though the more elastic micro- and macro-economic cost components may be extraneously beyond the

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_10

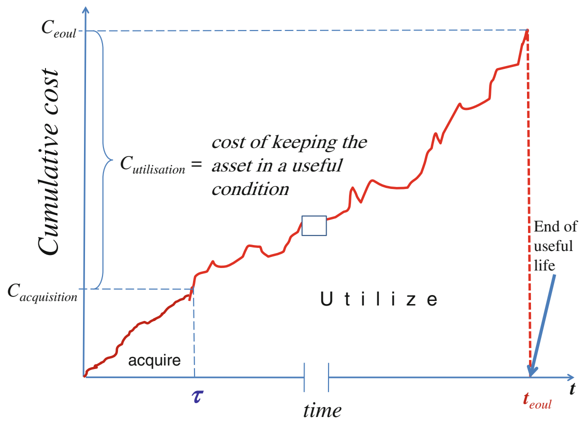


Fig. 1 An illustration of cumulative cost profile for an asset

control of the firm. As illustrated in Fig. 1, the cumulative cost associated with utilising a CMM can be very significant over the useful life of the asset. The utilisation cost, $C_{utilisation}$, in the interval $\tau < t \leq t_{eoul}$, depicts the combined costs of using and sustaining the machine in the condition necessary to deliver the aggregate levels of economic, environmental and social values demanded, often *ad valorem*, by the asset stakeholders over the useful life of the CMM. Environmental and social values are generally qualitative in nature and not easily measured, hence the convention is to determine the end-of-useful in terms of readily measurable quantitative economic values and costs.

As with any asset deployed as a means to an end, the costs associated with utilising a CMM are strongly influenced by the condition of the machine, and the condition must be described relative to the level of service required from the machine. The level of service demanded essentially encompasses the desired economic, environmental and social values, and strictly speaking, this also means that the condition of the machine must be stated in economic, environmental and social terms. Although the cost of acquiring the machine, that is, $C_{acquisition}$ may represent a small percentage of the cumulative cost as depicted in Fig. 1, however, the decisions made during acquisition determine upfront, the elements constituting the utilisation cost, $C_{utilisation}$ over the useful life of the asset. Whereas the decisions made during acquisition of the CMM inherently presume certain levels of technical/technological and financial risks and operational scenarios but, during the utilisation of the asset, uncertainties may arise from:

i. the vagaries of business demands,
ii. non-homogeneous rock faces associated with unpredictable underground mining environments, and
iii. changes in the firm's organisational and human behaviours.

These risks and uncertainties, nonetheless, can profoundly influence the utilisation, and hence the condition of the machine. In essence, the manner in which the CMM is utilised influences the condition of the asset and vice versa. During the utilisation phase, the first level condition assessment often involves human visual inspections of asset. The more sophisticated condition assessments include measurements, manipulation and analyses of signals arising from pressure, temperature or other types of sensors attached to the machine. Information derived from monitoring the signals may be combined with visual inspections to indicate the condition of a CMM.

Human beings are endowed with natural ability to concurrently apply their senses to identify, multiplex, track and interpret different signals to provide useful descriptions of what they observe. Human beings possess intuition, that is, the ability to match what their senses detect to incidents that have occurred in the past, and to extrapolate into the immediate future. On the one hand, intuition may be enhanced as a person encounters or experiences similar situations, and may result in increased knowledge gained through experience. On the other hand, sustained experience of a particular environment may also lead to intransigence, bias, and narrow-minded intuition. The natural endowment of multiplexed senses and experience means that a person affected by the operating environment can often 'feel' the condition of a machine in a manner that may remain tacit to the individual. Nevertheless, such tacit and experiential knowledge can be used to augment data and information derived from the measurement of physical parameters, and applied to assess the condition of an engineering asset. This paper discusses the application of tacit and experiential knowledge of operators and maintainers towards assessment of the condition of CMM's deployed in underground operations.

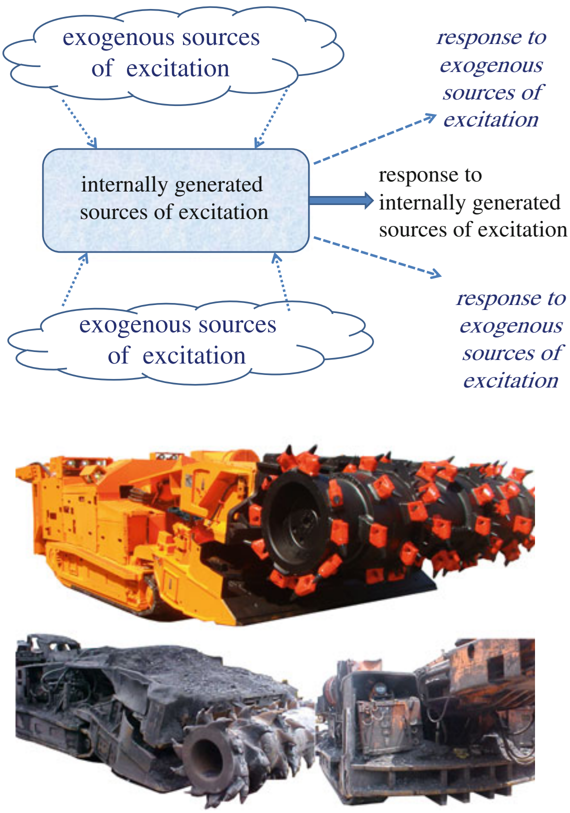
2 Reliability and Condition Assessment

2.1 The Continuous Mining Machine as a Dynamic System

As depicted in the diagram, and pictures shown in Fig. 2, a typical CMM is an engineering system that operates in underground mining environments, and the condition of any operating CMM at any instant in time may be characterised by signals internally generated by the machine, as well as other sources of excitation signals arising from the environment that surrounds the machine. The CMM fundamentally behaves as an active filter and its response will manifest nonlinearities inherent in both the machine and the operating environment.

Thus, in order to adequately describe the operating condition of a machine, it may be necessary to monitor a wide range of excitation and response signals, this, in turn will require concurrent sensing, measurement and tracking of many sources of signals. This is often not practical in many situations, simply because the full cost of attaching various types of sensors and the associated analytics may be prohibitive. Thus the tendency is to track response signals through independent measurements of effects such as acoustic noise generated from the vibration of the machine, and/or the measurement of temperature/pressure at selected points on the

Fig. 2 Dynamic system depiction and pictures (courtesy of Joyglobal) of continuous mining machine



machine, and/or the sampling oils embedded to lubricate various parts of the machine, and/or even taking photographic images of the machine.

From both statistics and dynamic systems theories, the complete range of excitation and response signals that may be necessary to fully characterise the condition of an operating CM may not represent an *ergodic* set of random variables. Although incomplete characterisation of the excitation and response signals of a dynamic system can lead to suboptimal assessment of the condition of the system, however, statistical models combined with domain knowledge can result in useful assessments of machine condition (cf: [17]). In underground mining environments, the sources of acoustic noise and vibration may be neither ergodic nor stationary, thus explicit measurements and empirical analyses of the associated sensor signals become very complicated for the CMM user, operator, or maintainer. Furthermore, the sources of excitations that influence the condition of a machine may be aggregated in such a way that each effect may not be mutually exclusive. For example, the vibration of the machine whilst in operation may generate associated acoustic noise, whilst concurrently influencing the ambient temperature, pressure, and other parameters. Thus, the acoustic noise and vibration signals may be correlated, as well to the signals from temperature, pressure, and other parameters. This means that there are many internal and surrounding influences on different parts of the machine, and their interaction aggregate to determine the condition of machine [33].

2.2 Reliability and Condition Monitoring

A synonym for reliability is dependability, and the general understanding of reliability is trustworthiness. A reliable CMM may be trusted to provide "…consistently good performance" [13], thus reliability tends to be included as a performance measure for a machine. Technically, reliability may be defined as the probability or chance that a machine will operate as ***intended*** within a specified ***time period*** and without ***failure*** under the confines of a ***surrounding*** or ***operating environment*** (cf: [6]). The words highlighted in bold italics indicate the four aspects that need to be monitored to succinctly describe the reliability of a machine. The first aspect is ***intention***, a difficult to describe quality that nebulously encapsulates the *ad valorem* aggregation of continuously changing economic, environmental and social values demanded by the various stakeholders to the machine. For an asset like a CMM, ***intention*** may be simplified and technically stated, for example, as the desired tonnes of run-of-mine produced by the CMM.

The second aspect is ***time period***, a quantity that can provide a better description of desired performance. For instance, a clearer statement of intention could be the desired tonnes of run-of-mine produced within a given time period. The third aspect is ***failure***, and from an asset management viewpoint, the description of failure can also be subjective; for example, has the CMM failed if it delivers less tonnes of run-of-mine within the stated time period? With this line of thought, a more strict description of intention could specify the tonnes of run-of-mine produced by the CMM, over a given time interval, and without failure. This means that the description of failure needs to be unambiguous and succinct. Often, the *ad valorem* imperative allows for the specification of acceptable failure modes, especially when the fourth aspect, s*urrounding* or *operating environment* is described as 'normal' operating conditions.

During utilisation, it is understandable that a CMM may deliver less tonnes of run-of-mine either due to a component malfunction or due to 'abnormal' operating conditions, or both, since, for example, hard rock may affect the efficiency of the cutterhead (see Fig. 2). This prompts the question as to what excitation and response signals respectively represent 'normal' and 'abnormal' operating conditions? This implies that the description of *operating environment* can be very qualitatively subjective, highly dependent on the person's intuition, knowledge and experience of the environment in which the asset operates. The ramifications of the three subjective aspects means that in practice, reliability is more readily understood by counting the number of instances that the machine has not delivered what we actually want when we want. The argument here is that the condition of an asset derives from the basic definition of reliability, therefore, the condition of a CMM may be assessed, first, by succinctly describing, and second, by appropriately monitoring

i. *intention*,
ii. *time period,*
iii. *failure*, and
iv. *surrounding/operating environment.*

2.3 Condition Monitoring, Diagnostics and Prognostics

In essence, what we really want is for an asset to provide the means to achieve the outcome intended, when the outcome is needed, and at the level the outcome is desired. We also expect that the asset will remain in a condition to deliver the desired levels of service when required. An asset may be acquired and commissioned (i.e., deployed) to be utilised for a specific purpose. If the asset is utilised in other ways, then the asset condition and reliability may both be compromised. Similarly the reliability of the asset may be compromised if the conditions of use change, or the operating environment changes, or if the duration of use becomes uncontrolled. Once commissioned, the operational reliability of an asset depends on its condition, how it is utilised, when it is utilised and the environment within which it is utilised. For a continuous mining machine, this means that the underground environment within which it operates strongly determines its condition and reliability [9, 19].

In the underground environment, we can expect that a CMM will operate as intended, so that *intention* may be concisely measured as throughput, e.g., tonnes per agreed time interval. The ideal situation would be that all stakeholders (i.e., operators, maintainers, managers, vendors, etc.) agree on the definitions of *failure* since there are a number of ways that the machine can fail to satisfy each stakeholder. Although there are well established methods (cf: [8]) to identify the technical failure modes apriori, however, it is not uncommon for the user, operator, maintainer and original equipment manufacturer to disagree on the definition of failure, especially as the language used to classify technical failure modes may be colloquial. A key issue for an asset manager is the creation of value, hence for brevity here, the failure of a CMM may be classified in two ways viz:

i. capability failure, i.e., complete loss of CMM productive capacity resulting in no throughput; and
ii. functional failure, reduced capability resulting in CMM productivity below the desired throughput.

As a quantitative variable, the time period during which the machine is expected to perform as desired (given acceptable failure modes) may be readily specified in appropriate units (i.e., hours, months, etc.); then, in order to assess the condition of the CMM, the only remaining aspect is to obtain a useful description of the *operating* *environment* surrounding the machine. It is in this regard that acoustic noise, pressure, temperature and vibration signals, as well as oil samples are typically monitored to obtain some indication of the condition of a CMM. The fundamental assumption is that these signals indicate how the machine dynamically responds to the excitation due to operating environment. In many situations, the cost of installing appropriate sensors, measuring and acquiring the presumed response signals may not only be prohibitive but also, the ability to interpret data arising from condition monitoring devices often requires a reasonable understanding of the behaviour of dynamic systems and statistical modelling. Thus, the knowledge and skill required to manipulate and analyse the signals places considerable burden on the efforts of typical operators and maintainers of CMM's. For instance, an operator may be aware of the consequence of a functional failure mode but, based on experience, the operator may still be willing to take a chance to operate the machine to ensure that the asset continuously provides stipulated value.

A number of references [e.g., 3–5, 14, 21] discuss the subject of condition monitoring and the application to improve component reliability and condition-based maintenance of equipment. For component reliability (e.g., cutterhead in a CMM), inspection data are assigned relative rankings mapped against failure rates so as to differentiate between 'bad', 'acceptable', and 'good' component conditions. Such data may also be extrapolated to identify and classify components mostly influence the operating condition of a machine. Conventionally, condition monitoring data is used to determine preventative maintenance actions that can minimise the chance of equipment failure, or to establish appropriate corrective maintenance actions in the event of failure of repairable equipment. Where the firm organisational behaviour makes it possible, condition monitoring data may be applied to revise the operating philosophy even though operators tend to be reluctant to do so. Condition monitoring data are also applied to

i. diagnose and isolate failure modes [20]; as well as to
ii. predict future state of equipment based on evidence of its current state; and to
iii. estimate the remaining life of components [16, 18, 25, 26, 28]; so as to
iv. determine when and how restoration can be done [29].

The shift in paradigm not only includes detecting the incidence of fault modes and identifying their respective impacts on asset performance but also, in estimating how long the asset can continue to provide stakeholder value under fault conditions [7, 11, 12]. This survival aspect presents interesting challenges, especially to the relationship between users and manufacturers of continuous mining machines.

2.4 Knowledge-Based Condition Assessment

When referring to condition assessment, information derived from analyses of response signals from acoustic, pressure, temperature or vibration sensors are commonly accepted, even though the characterisation provided by such information may be suboptimal. The notion of using an individual's experience, feelings or intuition often tends to be treated with disregard, suspicion, and sometimes rejected. Such contempt may present a barrier to the flow of tacit knowledge that exists in the form of intuition and personal experience [32], and the scepticism hampers the extraction of tacit knowledge into structured forms [31] that can enhance intelligence for more optimal condition assessment [10, 24]. Tacit knowledge needs to be transferred together with the context that gave rise to the experience [15, 30]. In theory, a change in context creates new information about existing knowledge.

An operator, a maintainer, or an engineer in an underground mine may experience the same environment in their respective contexts, so each person may describe the operating condition of a CMM differently. This means that new information relating to the condition of a CMM also contains a measure of interpretation and understanding relative to the operating environment of a machine. Thus when extracting tacit information from continuous miner users it is imperative to also extract their experience which forms the context in which their tacit information can be interpreted. Although tacit knowledge needs to be objective, however, the context within which the tacit information is formed is equally essential [1, 27], so as to minimise suboptimal assessments of asset condition.

3 Research

Figure 3 depicts the various categories of knowledge necessary towards optimal assessment of the condition of an asset. From asset condition assessment viewpoint, some useful approaches to extract tacit knowledge from experience [2] include asking appropriate stakeholding respondents to:

i. indicate how the asset is utilised;
ii. describe the respective values they have obtained, and expect from the asset;

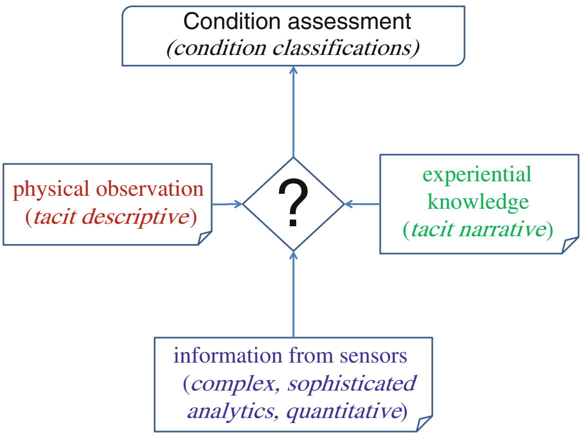


Fig. 3 Integrating experiential knowledge for condition assessment

iii. discuss the levels of risks and costs they have entertained and are willing to accept;
iv. indicate known failure modes, highlighting any outlying events;
v. describe operating environment scenarios for the asset;
vi. narrate their general experiences in related to the asset; and to
vii. share stories they may have heard from other peoples' experiences with the asset.

These approaches were adapted to conduct semi-structured interviews of users of continuous mining machines from mining firms A and B. During the interviews, the interviewer placed emphasis on mapping interviewee experiences against the four aspects of reliability. In firm A, only two interviewees from two different mining operations were available to attend the interview. In firm B, two interviewees were available from two different shafts of one mine and a third interviewee from another mining operation of the firm. Another available respondent from a machine support services firm declined the interview but provided narratives in writing. The six respondents were engineers but five were directly responsible for 31 continuous mining machines out of a fleet comprising 215 machines for one original equipment manufacturer supplying the region. The transcribed narrative responses of the interviewees are briefly summarised as follows.

4 Integrating Experiential Knowledge for Condition Assessment

All interviewees surmised that their CMM's were used for mining coal. The underground conditions and ventilation legislation require that the machines be used only for the intended purpose. The respondents generally agreed that the user regards failure as the condition where no production is possible from the CMM. Respondents commented that component failures often manifest when they are close to achieving the production targets for the week. Three interviewees commented that when condition monitoring indicates component malfunction, where possible, they would promptly replace the affected component but operate the machine to achieve the shift production target. A respondent cited an example where the noise from one gearbox significantly increased but, the machine was not stopped during the production interval. In this instance, the functional failure of a component was evident but not regarded as a failure of the CMM, and the operators continued to use the machine in order to achieve the throughput target. Another interviewee cited the high turnover of torque shafts but, in the view of the machine support engineer, the repair and replacement costs for such functional failures raised significant concerns for the original equipment manufacturer.

The respondents' feedback on failure highlight that the operators' combine their experiences and knowledge of the environment to determine if the CMM should continue operating, even if it means overriding the information from physical sensors. The impression from the respondents is that operators' experience of history is often applied to mitigate uncertainty, especially with regard to the mining conditions. Interviewees commented that the 'gut feel' of a person who has worked with CMMs for many years ought to be regarded with credibility. The credibility of the experience is significant for persons who also have specific knowledge of the mine, and the respondents recommended that such specific experience should be considered as lead evidence while assessing the condition of a CMM. The respondents commented that although the operator often observes incipient changes, however, the tacit nature of the experience often obscures credibility of the narrative. Rather, the practice tends to ascribe higher relevance to quantitative data from vibration sensors, even though the persons who manipulate and analyse signals arising from such sensors may be remote from the CMM's operating environment.

5 Concluding Remarks

The engineers interviewed signify that the opinion of experienced operators in specific environments is pertinent to assessing the conditions of CMMs. The implication is that information provided by experienced CMM operators should be treated with high relevance while assessing the condition of a CMM. Although so called expert systems employing artificial intelligence algorithms are well established and applied, however, the interviewees reiterated that, with the high levels of uncertainty prevailing in underground mining environments, the relevance of operator experiential knowledge of specific conditions remains significant. With this in mind, the pilot study will be extended to determine empirical weightings of the opinions of CMM operators in relation to machine condition classifications.

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Extraction of Principal Components from Multiple Statistical Features for Slurry Pump Performance Degradation Assessment

Peter W. Tse and Dong Wang

Abstract Slurry pumps are one of the most common machines in oil sand pumping operations to pump abrasive and erosive solids and liquids from one location to another location. The impeller of a slurry pump is prone to suffer severe wear which may cause slurry pump breakdown and result in huge economic loss. Therefore, it is necessary to construct a health indicator to monitor the health evolution of the impeller. In this paper, raw slurry pump vibration signals are reprocessed through vibration signal analysis and low-pass filtering. Then, multiple statistical features are extracted from time domain and frequency domain, respectively. It should be noted that these statistical features may be correlated and redundant. To reduce the dimensionality of these statistical features, principal component analysis is conducted on these statistical features to discover significant features, namely principal components, for tracking slurry pump health condition. Industrial slurry pump vibration signals are investigated to illustrate how the developed method works. The results show that the deteriorating trend of slurry pump impeller can be well evaluated by the developed method.

1 Introduction

Slurry pumps are one of the most common machines used in oil sand pumping operations to pump the mixtures of abrasive and erosive solids and liquids from one location to another location. Continuous erosion and abrasion of slurry pump impeller may cause slurry pump breakdown and result in huge economic loss. To prevent slurry pump breakdown, it is necessary to assess slurry pump performance degradation.

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_11

Performance degradation assessment is used to describe how far current machine health condition deviates from its normal health condition. Some typical examples are illustrated as follows. Reference [1] applied the Morlet wavelet and self organizing map to assess bearing performance degradation. Reference [2] applied discrete wavelet transform to track gear health condition, whilst [3] used wavelet packet node energy features to train and test hidden Markov models for bearing performance degradation assessment. Hidden Markov models were also used by [4] to evaluate gear health condition deterioration. Reference [5] used wavelet packet node energy features to train support vector data description for tracking bearing health condition. Wang et al. [6] extracted multiple statistical features from gear residual error signals and used these statistical features to train support vector data description for gear health condition evaluation. The candidates for the use of support vector data description for performance degradation assessment are fuzzy support vector data description [7] and rough support vector data description [8].

According to our literature review, papers related to slurry pump impeller health condition assessment are very limited. Some researchers [9] introduced artificial damages to impellers and collected vibration signals from the slurry pump with these damages. Based on the collected data, some intelligent slurry pump impeller fault diagnosis methods were developed. The combination of support vector machine, a novel data cleaning algorithm and a classical sequential backward feature selection was developed by Qu and Zuo [10] to identify four different impeller damages and their associated damage levels. Following this, [11] applied least square support vector regression to quantitatively assess slurry pump impeller health condition. Zho et al. [12] improved a neighbourhood rough set model and used it to select significant features. Then, the combination of the half, full spectra and principal component analysis was used to construct a monotonic health indicator for slurry pump impeller health evaluation. Even though their methods and results are interesting and attracting, artificially produced data were used in their work. Artificial data do not naturally express the true wear process of slurry pump impeller. To investigate the relationship between the natural wear process and slurry pump impeller health evaluation, one of the co-authors in this paper went to an oil sand company to collect natural impeller wear data which were investigated by [13–15]. In their work, the remaining useful life of slurry pump impeller was estimated. Prior to estimation of impeller remaining useful life, performance degradation assessment of slurry pump impeller is used as a basis for prognosis.

In this paper, we continue to explore impeller performance degradation assessment using principal component analysis. The major contribution of this paper is that multiple statistical features are reduced to a single feature for reflecting the health evolution of slurry pump impeller. This work is different from the research work done previously as mentioned above. In the previous work, the indicator of vibration energy was selected from its frequency spectrum domain as the dominant health indicator. Here, we use principal component analysis to evaluate a total of 18 health indicators into one single indicator to construct the required fault trend.

2 Extraction of Principal Components from Multiple Statistical Features for Slurry Pump Performance Degradation Assessment

Vibration analysis is a convenient and effective way to monitor machine health condition and diagnose machine faults [16]. In this paper, we focus on health condition monitoring of slurry pump impeller. In other words, a health indicator is required to be built for describing the health evolution of slurry pump impeller.

The oil sand pump was driven by a motor with the rotation frequency equal to f_{m} = 26 Hz. Because the oil sand pump was stepped down through a gearbox, the pump rotation frequency f_{p} was approximately equal to 6.62 Hz. The vane-passing frequency f_{vpf} was that 4 blades on the impeller multiply the pump rotation frequency and equal to 26.48 Hz. The gear meshing frequency f_{gmf} was equal to 362 Hz. The pump vibration measurements were collected by using the smart asset management system (SAMS) software developed in the Smart Engineering Asset Management Laboratory. The data acquisition equipment consisting of a National Instrument (NI) DAQ 9172 and a DAQ module NI 9234 was used. Four accelerometers were mounted at four different locations of the slurry pump, where the PCB 352A60 accelerometers (S1 and S2) were mounted on 'casing lower' and 'casing discharge' and the PCB 352C18 accelerometers (S3 and S4) were mounted on the 'suction and discharge pipes'. The data were recorded from March to June and the total number of the vibration measurements N was 1,096. In order to identify each measurement, these measurements were numbered by document numbers from 1 to 1,101. The sampling frequency was set to 51,200 Hz. For each measurement, the vibration signal with the length N of 51,200 samples was collected. The data collected from the suction pipe was used for the analyses in this paper.

First, denote that x is a centered temporal vibration signal and y is its corresponding frequency spectrum. 9 statistical features are extracted from the raw temporal vibration signals and they are represented by $(F_1, F_2, \ldots, F_9)$. The equations for these 9 statistical features are tabulated in Table 1. Then, 9 more statistical features are extracted from the frequency spectra of the raw temporal vibration signals and they are represented by $(F_{10}, F_{11}, \ldots, F_{18})$. The equations for these 9 more statistical features are the same with those used for quantifying the temporal vibration signals. The 18 statistical features extracted from slurry pump vibration signals are plotted in Fig. 1a–r, respectively.

From the statistical features shown in Fig. 1, it is difficult to find any trend which can be used to track the deterioration of slurry pump impeller. Further, these statistical features shown in Fig. 1 are analyzed by principal component analysis. Principal component analysis is used to reduce the dimensionality of the feature vector and generate new significant features, namely principal components, from the feature vector [17]. Denote L successive slurry pump vibration measurements as $x_k(t)$, $k = 1, 2, \ldots, L$. Therefore, a feature matrix is constructed by considering the different vibration measurements:

Table 1 The statistical features used for quantifying slurry pump vibration signals

Mean value: $F_1 = \frac{1}{N}\sum_{i=1}^{N} x_i$	Root mean square (RMS): $F_2 = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}$
$F_3 = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(x_i - \frac{1}{N}\sum_{i=1}^{N} x_i\right)^2}$	Skewness: $F_4 = \frac{N\sum_{i=1}^{N} x_i - N\sum_{i=1}^{N} x_i}{\left(\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x_i - \frac{1}{N}\sum_{i=1}^{N}(x_i)\right)^2}\right)^3}$
Kurtosis: $F_5 = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(x_i - \frac{1}{N}\sum_{i=1}^{N} x_i\right)^4}{\left(\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x_i - \frac{1}{N}\sum_{i=1}^{N} x_i\right)^2}\right)^4}$	Crest factor (CF): $F_6 = \frac{\max(\lvert x_i \rvert)}{\sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}}$
Clearance factor (CLF) $F_7 = \frac{\max(\lvert x_i \rvert)}{\left(\sqrt{\frac{1}{N}\sum_{i=1}^{N}\sqrt{\lvert x_i \rvert}}\right)^2}$	Shape factor (SF): $F_8 = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}}{\frac{1}{N}\sum_{i=1}^{N} \lvert x_i \rvert}$
Impulse factor (IF): $F_9 = \frac{\max(\lvert x_i \rvert)}{\sqrt{\frac{1}{N}\sum_{i=1}^{N} \lvert x_i \rvert}}$	

Note The following 9 equations (from F_1 to F_9) are used to quantify the raw temporal slurry pump vibration signals; the same 9 equations (from F_{10} to F_{18}) are also used to quantify the frequency spectra of the raw temporal slurry pump vibration signals

$$\mathbf{X} = \begin{bmatrix} F_{1,1}, & F_{1,2}, \ldots F_{1,18} \\ F_{2,1}, & F_{2,2}, \ldots, F_{2,18} \\ \vdots & \vdots \\ F_{k,1}, & F_{k,2}, \ldots, F_{k,18} \\ \vdots & \vdots \\ F_{L,1}, & F_{L,2}, \ldots, F_{L,18} \end{bmatrix} \tag{1}$$

From Eq. (1), it is seen that the feature matrix comes from an 18 dimensional space. The aim of principal component analysis is to transform the 18 dimensional space to a low dimensional orthogonal space with dimensionality $p < 18$. Each of the new features is called a principal component. Besides, the feature matrix transformed to the first new coordinate has the greatest variance. The feature matrix transformed to the second new coordinate has the second greatest variance, and so on. Suppose that each column of Eq. (1) has zero mean and unit variance, which can be easily satisfied. Mathematically, the above problem is written as the following optimization model:

$$\begin{aligned} &\mathbf{w} = \arg\max\left(\|\mathbf{X}\mathbf{w}\|^2\right) = \arg\max\left(\mathbf{w}^T\mathbf{X}^T\mathbf{X}\mathbf{w}\right), \\ &\text{subject} \quad \text{to} \quad \|\mathbf{w}\| = 1 \end{aligned} \tag{2}$$

where T is the transpose operator.

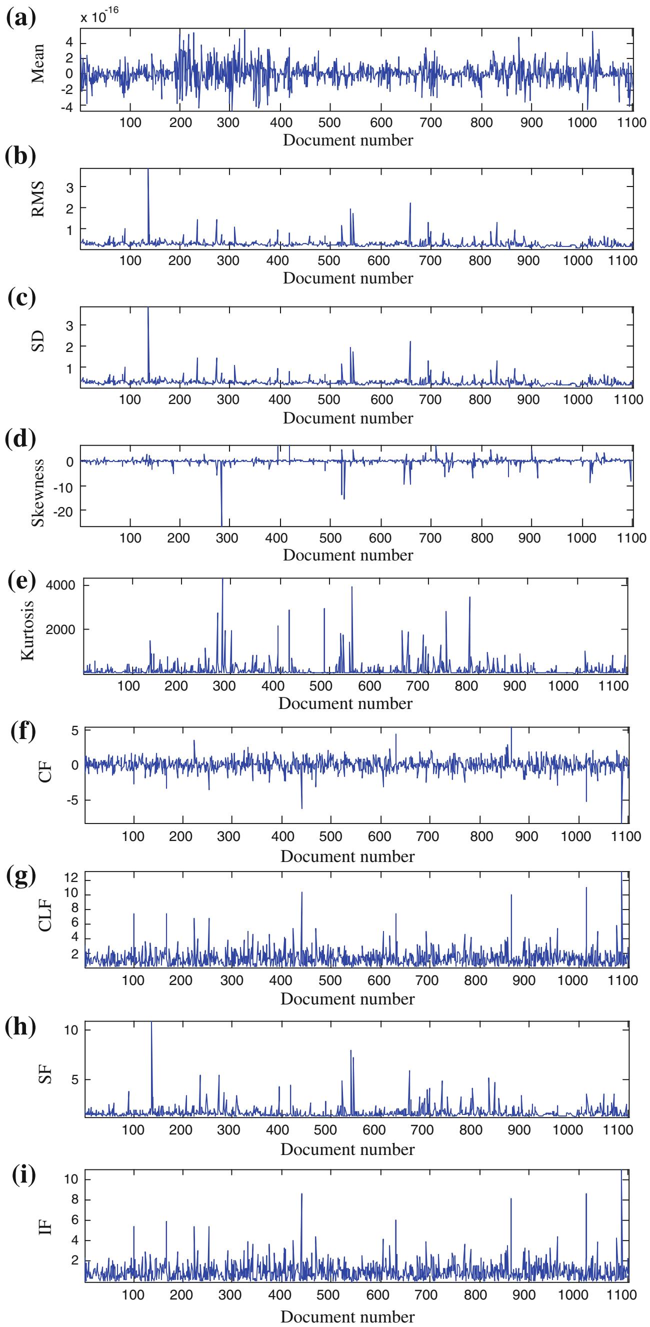

Fig. 1 Statistical features directly extracted from the raw temporal slurry pump vibration signals: **a** Mean; **b** RMS; **c** SD; **d** Skewness for F_1 to F_4 respectively. **e** Kurtosis; **f** CF; **g** CLF; **h** SF; **i** IF for F_5 to F_9 respectively. Statistical features directly extracted from the frequency spectra of the raw temporal slurry pump vibration signals: **j** Mean; **k** RMS; **l** SD; **m** Skewness for F_{10} to F_{13} respectively. **n** Kurtosis; **o** CF; **p** CLF; **q** SF; **r** IF for F_{14} to F_{18} respectively

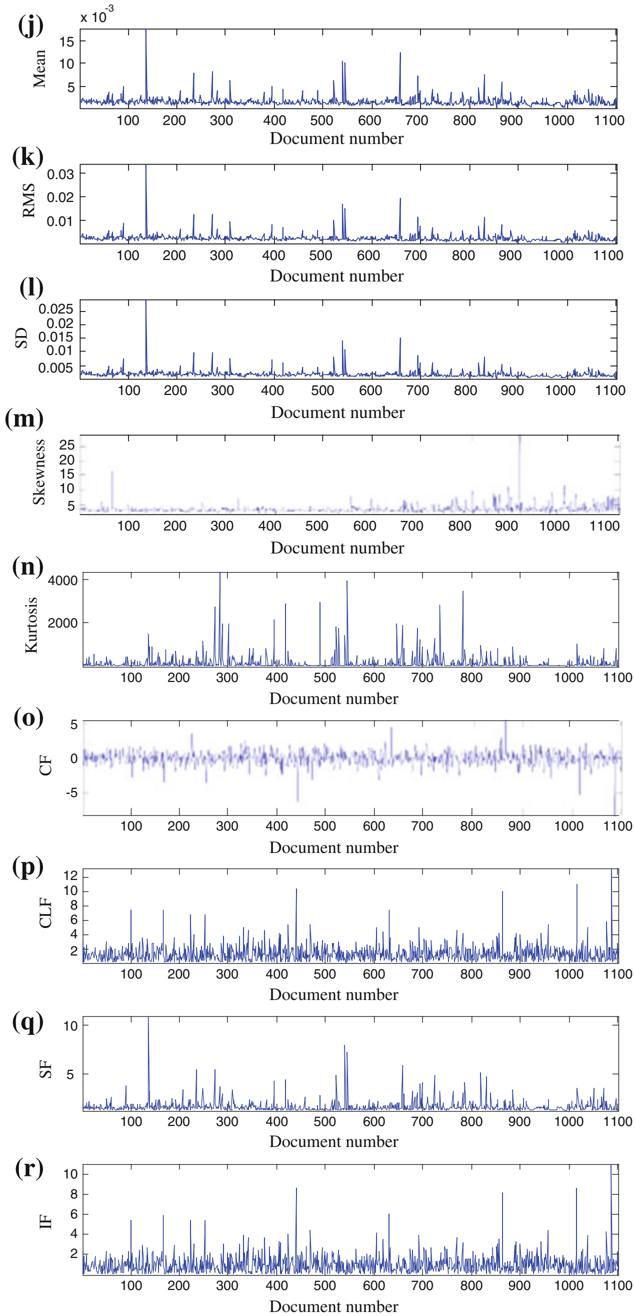

Fig. 1 (continued)

The Lagrange function of Eq. (2) is constructed as:

$$R(\mathbf{w}, \lambda) = \mathbf{w}^T \mathbf{X}^T \mathbf{X} \mathbf{w} - \lambda \mathbf{w}^T \mathbf{w}, \tag{3}$$

where λ is the Lagrange multiplier. The first partial derivative of *R* with respect to **w** is derived as follows:

$$\frac{\delta R(\mathbf{w}, \lambda)}{\delta \mathbf{w}} = 2\mathbf{X}^T \mathbf{X} \mathbf{w} - 2\lambda \mathbf{w}. \tag{4}$$

Let Eq. (4) be equal to zero. The relationship between **w** and the Lagrange multiplier is derived as:

$$\mathbf{X}^T \mathbf{X} \mathbf{w} = \lambda \mathbf{w}. \tag{5}$$

Solving Eq. (5) can find the eigenvalues and eigenvectors of the symmetric matrix $\mathbf{X}^T \mathbf{X}$. Suppose that the first column of **w** is the eigenvector corresponding to the largest eigenvalue, the second column of **w** is the eigenvector corresponding to the second largest eigenvalue, and so on. Therefore, the feature matrix can be mapped into a new coordinate system as follows:

$$\mathbf{t} = \mathbf{X}\mathbf{w}. \tag{6}$$

Therefore, the first column of **t** is the first principal component t_1, the second column of **t** is the second principal component t_2, and so on. When principal component analysis is used, the number of the principal components is required to be determined. In this paper, the number of the principal components is established by calculating the variances of the principal components. The variances of the resulting principal components and the first principal component are plotted in Fig. 2a, b, respectively. The first principal component is selected because the variance of the first principal component has the largest slope. However, the first principal component shown in Fig. 2b has no any obvious degradation trend. To better exhibit the trend of the first principal component, the mean of the first component (MFCP) is calculated as follows:

$$\mathrm{MFCP}(k) = \frac{\sum_1^k t_1(k)}{k}, \quad k = 1, 2, \ldots, L. \tag{7}$$

According to the definition of Eq. (7), MFCP is shown in Fig. 2c, in which the degradation trend of the slurry pump impeller is not easy to be found.

In order to enhance the signal to noise ratio of the raw slurry pump vibration signals, a low-pass filter is used to pre-process the raw slurry pump vibration signals and retain the vane-passing frequency and its harmonics. The band-pass cut-off frequency was set to 100 Hz. Then, the 18 statistical features are extracted from the filtered temporal vibration signals and their frequency spectra, respectively.

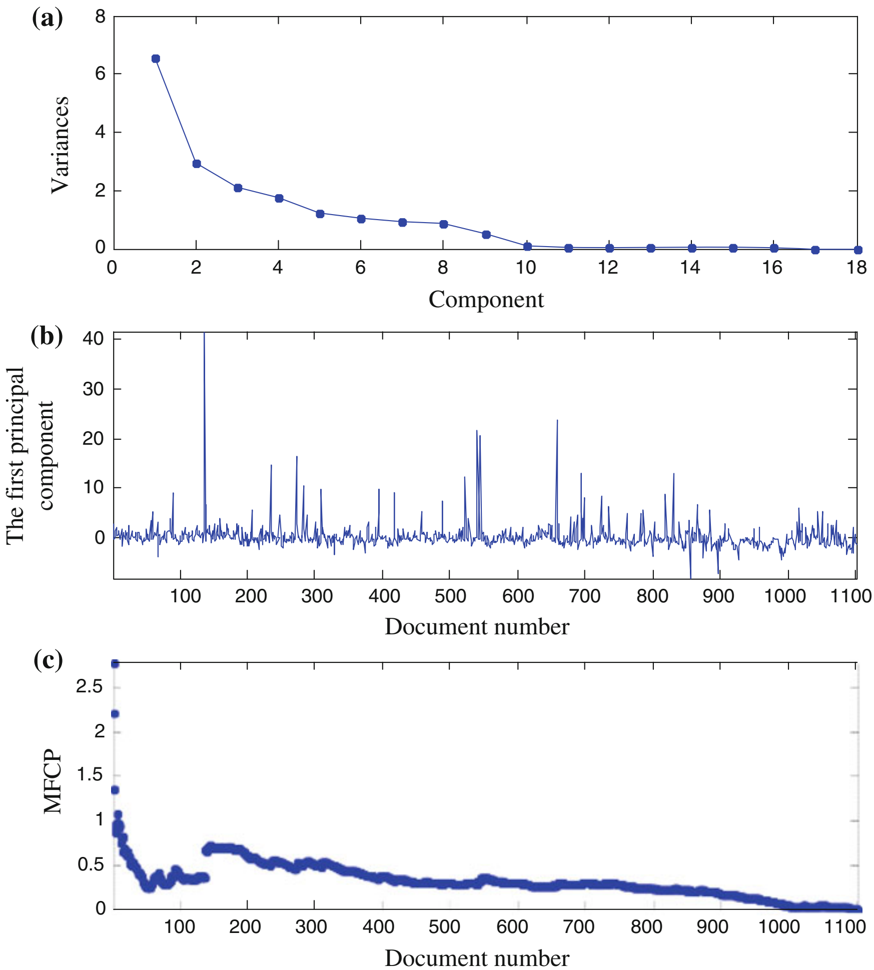

Fig. 2 Slurry pump impeller performance degradation assessment by using the statistical features shown in Fig. 1 and principal component analysis on the collected raw data but *without applying the low-pass filter*: **a** the variances of principal components; **b** the first principal component; **c** the mean of the first principal component

The principal component analysis was applied to process these 18 statistical features and the results are shown in Fig. 3a, b. The first principal component is chosen because its variance has the largest slope. From Fig. 3a, b, it is found that the first principal component has an obvious trend to describe the impeller degradation after the raw slurry pump vibration signals were filtered by the low-pass filter. Besides, the MFCP shown in Fig. 3c has a more obvious degradation trend. Compared with the impeller degradation trend shown in Fig. 2b, c, the principal component analysis of the statistical features calculated from the filtered vibration signals is more effective in exhibiting slurry pump degradation trend.

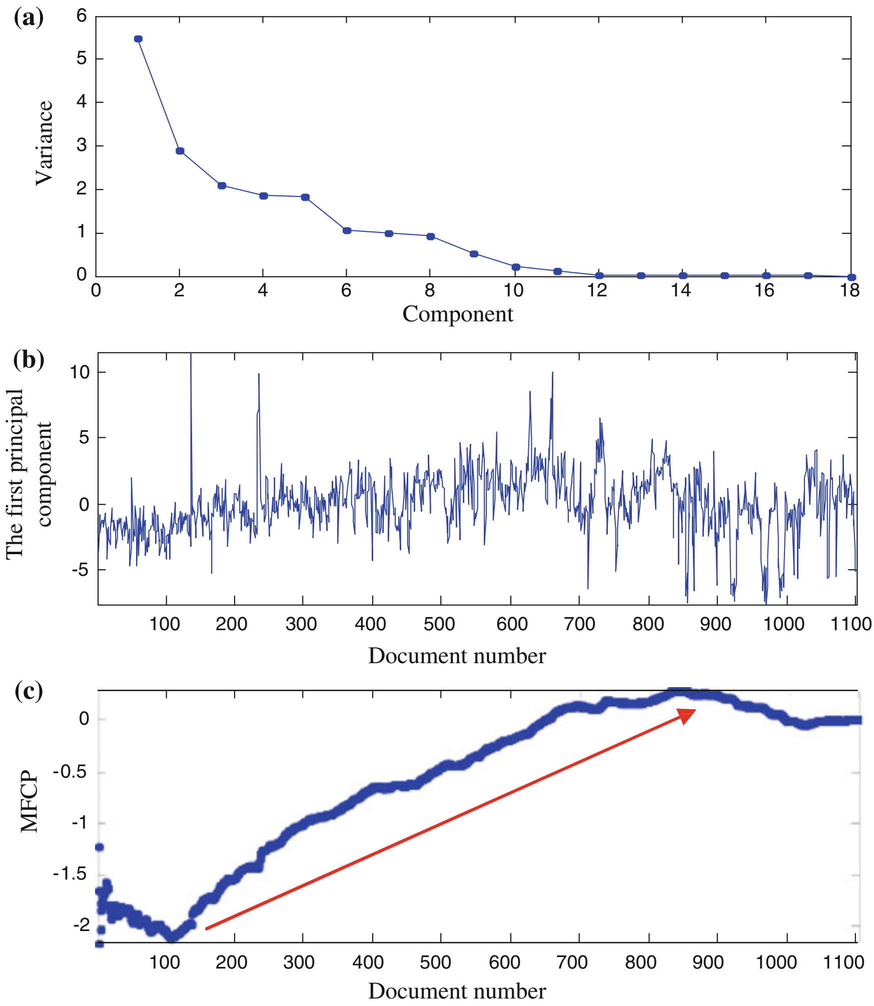

Fig. 3 Slurry pump impeller performance degradation assessment by using the developed method and the data *filtered by a low-pass filter*: **a** the variances of principal components; **b** the first principal component; **c** the mean of the first principal component

3 Conclusions

In this paper, a method for assessing slurry pump performance degradation was developed. First, 18 statistical features were extracted from the raw slurry pump vibration signals. The results show that any of the 18 statistical features has no obvious degradation trend. Further, principal component analysis was applied to generate new statistical features from the 18 statistical features. The first principal component was selected because its variance has the largest slope. However, the first principal component does not show a degradation trend. In order to enhance the signal to noise ratio of the raw vibration signals, a low-pass filter was specifically designed to retain the frequency band containing the vane-passing frequency and its harmonics. Then, the principal component analysis was conducted on the 18 statistical features extracted from the signals filtered by the low-pass filter. With the help of the low-pass filtering and principal component analysis, the first principal component shows an obvious degradation trend, which can be used to track the health evolution of the slurry pump impeller.

Acknowledgment The work described in this paper was fully supported by the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. CityU 122513) and a grant from the City University of Hong Kong (Project No. 7004251).

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Further Reading

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Fault Detection of Wind Turbine Drivetrain Utilizing Power-Speed Characteristics

Md Rifat Shahriar, Longyan Wang, Man Shan Kan, Andy C.C. Tan and Gerard Ledwich

Abstract Wind energy, being the fastest growing renewable energy source in the present world, requires a large number of wind turbines to transform wind energy into electricity. One factor driving the cost of this energy is the reliable operation of these turbines. Therefore, it is a growing requirement within the wind farm community, to monitor the operation of the wind turbines on a continuous basis so that a possible fault can be detected ahead of time. As the wind turbine operates in an environment of constantly changing wind speed, it is a challenging task to design a fault detection technique which can accommodate the stochastic operational behavior of the turbines. Addressing this issue, this paper proposes a novel fault detection criterion which is robust against operational uncertainty, as well as having the ability to quantify severity level specifically of the drivetrain abnormality within an operating wind turbine. A benchmark model of wind turbine has been utilized to simulate drivetrain fault condition and effectiveness of the proposed technique has been tested accordingly. From the simulation result it can be concluded that the proposed criterion exhibits consistent performance for drivetrain faults for varying wind speed and has linear relationship with the fault severity level.

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_12

Keywords Wind turbine assets · Condition monitoring · Fault detection

1 Introduction

The decrease of the fossil fuel reserve and climate concerns leads the world to concentrate more on harvesting renewable energy. Among these renewable sources, wind power has the highest total installed capacity around the world after the hydropower. The global wind power generation capacity was 318.14 GW by the end of 2013 with an installation of 35 GW during the year 2013 [1]. This large amount of energy is produced through the continuous operation of more than 225,000 wind turbines (WTs) around the world [2]. The cost of the wind energy is dependent on the reliability of operation of the existing turbines. According to a survey, the operation and maintenance cost accounts for 10–30 % of the total cost of energy [3, 4]. Moreover, to meet the targeted electricity production, offshore wind farms are a strongly growing component with larger turbines which may not be accessible during part of the year. These large wind turbines exhibit greater failure rate which accounts for 25–30 % of the overall energy generation cost with a considerable component for unscheduled maintenance [5]. The overall cost of maintenance can be considerably reduced through the optimization of the existing operation and maintenance approach. This has the potential to reduce unscheduled maintenance, parts replacement cost and overall downtime and thus increases the reliability and cost effectiveness of wind energy.

At present, there are two commercial approaches available for the condition monitoring of WTs. One of these two is supervisory control and data acquisition (SCADA) system based while, the other one uses purpose-designed condition monitoring system (CMS) [6]. The SCADA is a conventional plant monitoring system used to monitor important plant parameters at an average interval of 10 min and send it to the control center, for recording and visualization, where a human operator usually monitors the operational behavior of the system and acts accordingly. This SCADA system, actually adopted from other industries, often does not sufficiently consider the particularities of WT operation, thus, causing false alarm. Moreover, there is a lack of data analysis tools for SCADA based WT monitoring system [6]. On the other hand, in-depth continuous monitoring as well as diagnosis of abnormal operation of a WT is possible using the CMSs, which is specially designed for the WTs. A number of CMSs are now available commercially to monitor tower, blades, bearings, gearbox and generator of a WT. To improve performance of the present CMSs, investigations are ongoing which have been summarized in [7]. Essentially, the capability of a condition monitoring system depends on the type of sensor used and associated signal processing methods applied to extract the condition related information from the sensor signal. The conventional CMSs perform the task of monitoring a WT by measuring vibration, acoustic emission (AE), process parameters like temperature and speed, gear oil contamination and strain. However, the electrical signature analysis (ESA) approach has also been employed recently for the condition monitoring and fault diagnosis of the WT. This technique uses electrical signals like current, voltage and power to monitor the condition of WT generator and drive train related components. No additional sensor is required for this technique as the electrical signals are readily available in a commercial WT. Moreover, it can be applied to diagnose both electrical and mechanical faults of a WT [4, 8–12].

The ESA based condition monitoring techniques, discussed in [4, 9, 12], proposed criterion parameters for online monitoring of the WT operational condition while diagnosis of abnormal operation was achieved by simply observing the variation of criterion parameters or time-frequency analysis of relevant electrical quantities. Yang et al. proposed the ratio of torque and speed of the generator as a criterion for detecting faults in the drivetrain of a permanent magnet synchronous generator (PMSG) based wind turbine [9]. Another publication suggested three criterion parameters, which are calculated using the current, voltage and power output of a WT and employed their patterns to identify and distinguish between electrical and mechanical faults of WT drive train containing a wound rotor induction generator [12]. As well, Yang in [4], proposed the instantaneous variance (IV) of electrical quantities as a criterion for condition monitoring and fault diagnosis of PMSG based WT. In that research, the IV of the power output was monitored for detecting abnormality in the WT drivetrain. Although the existing condition monitoring criteria, as discussed above, show sensitivity to any abrupt fault related change of WT operation, they suffer from two major shortcomings: (i) the criteria are not independent of the speed variation, i.e., the non-stationary operating nature of the wind turbine is not well accommodated while developing these criteria, and, (ii) direct measurement of fault severity level is not possible from the magnitude of the criteria. Considering these limitations of the previous research, a novel condition monitoring parameter, sensitive to fault severity as well as robust against the speed variation of WTs, is proposed in this paper. The usefulness of the proposed criterion parameter has also been validated using simulation results.

The remaining sections of this paper are organized as follows. In Sect. 2, a novel criterion for the continuous monitoring of WT drivetrain is proposed. Section 3 describes the wind turbine model that is used for the simulation experiments. It also describes the fault model that is utilized for validating the effectiveness of the proposed criterion. In Sect. 4, simulation results are presented along with necessary analysis and comparison with existing criterion. Section 5 contains the concluding remarks and future work plan.

2 Condition Monitoring Criterion

The criteria parameters, as developed in this paper, are based on the previously published research presented in [9]. A brief description of that development is presented here for ease of discussion. Consider a wind turbine (Fig. 1) based on

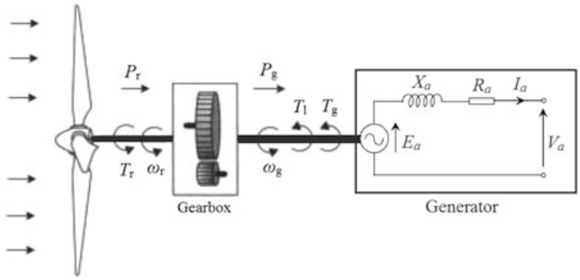

Fig. 1 A simplified diagram of wind turbine generator and drivetrain

synchronous generator where the wind power (P_r) received by the WT blade-rotor system is fed to the generator through a gearbox. The mechanical torque (T_r) of the rotor flows to the generator shaft and becomes T_g after experiencing losses in the drive train which is quantified as T_l. In case of higher capacity WTs torque, the loss can be neglected as it is small enough compared to T_r. Therefore, torque produced by the synchronous generator equates the rotor torque.

$$T_r \approx T_g \tag{1}$$

Using the approximation of negligible stator resistance (R_a) it is shown in [9] that,

$$T_r \propto \frac{\omega_g}{X_a} \tag{2}$$

where, ω_g and X_a are respectively angular speed and synchronous reactance of the generator.

Torque and speed transducers are used in [9] to get shaft torque and angular speed of the synchronous generator. However, indirect method of generator torque estimation is also available through the measurement of stator current, shaft angular position and magnetic flux. The condition monitoring criterion C is defined in [9] as a ratio of T_r and ω_r.

$$C = \frac{T_r}{\omega_r} \tag{3}$$

where, $\omega_r = \omega_g/N_g$ and N_g represents the gearbox ratio. As reported in [9], the WT drivetrain mechanical faults put a trace in C as torque and speed of the generator is affected by the faults. Again, using (2) and (3) the relationship between C and X_a can be found which implies that electrical faults occur in winding should also be detected by monitoring shape of C. The authors in [9] provided practical experimental results to support their claim. The experiments were performed on a laboratory prototype of WT synchronous generator drivetrain. Keeping the above mentioned technique in mind, let us consider the typical power-speed characteristics (Fig. 2) of a variable speed WT drawn for different wind speed (v_w), where the

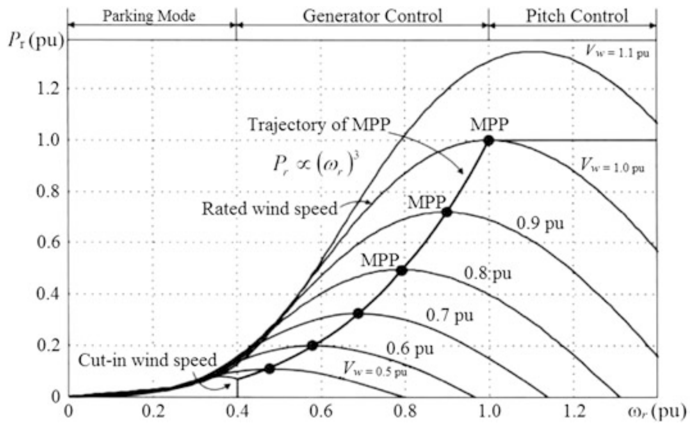

Fig. 2 Power-speed characteristics of a wind turbine at different wind speed [13]

quantities are expressed in per unit (p.u). Here, P_r and ω_r are the mechanical power and angular speed of the turbine respectively. It is evident that, for every wind speed (v_w) there is an optimum value of angular speed for which maximum power production is possible. These points in the curve are designated as the maximum power points (MPPs). To extract maximum available power from the wind at different wind speed, the WT must be operated on the trajectory of MPPs which can be represented by the following relationship [13].

$$P_r \propto (\omega_r)^3 \tag{4}$$

The mechanical power (P_r) can also be expressed in terms of the torque and angular speed.

$$P_r = T_r \omega_r \tag{5}$$

Using Eqs. (4), (5) and (1), the relationship between generator torque and speed can be readily obtained as,

$$T_g \propto \omega_g^2 \tag{6}$$

In fact, the control system of a WT performs the job of tracking MPPs according to Eq. (6) by controlling electrical loading of the generator. Equation (6) can be rewritten as,

$$T_g = K' \cdot \omega_g^2 \tag{7}$$

where K' is a turbine specific constant.

Now, using Eqs. (1) and (7) in Eq. (3), we get the following representation of condition monitoring criterion C.

$$C = N_g \cdot \left(\frac{T_g}{\omega_g}\right) = K' \cdot N_g \cdot \omega_g = K \cdot \omega_g \tag{8}$$

Here, K is also a constant. Equation (8) suggests that, the shape of criterion C would be similar to the generator speed. Therefore, it is possible to detect a drivetrain fault using C if the generator speed ω_g is affected by the fault. However, the fault related transient variation of the speed ω_g would be submerged in the overall speed signal collected by associated transducer. Moreover, in case of a variable speed WT the speed of the generator is not a constant value. Therefore, the possibility of detecting a drivetrain fault using C exists only after rigorous processing of its signal. It limits the use of C as a standalone criterion for fault detection while WT is in operation. To overcome this limitation, we are proposing a new criterion parameter, named as fault indicator (*FI*) hereafter, which is based on the relationship between T_g and ω_g as applied in the control system of WTs. Using Eqs. (4–7), the *FI* is defined as follows.

$$FI = \frac{d}{dt}\left(\frac{P_g}{\omega_g^3}\right) = \frac{d}{dt}\left(\frac{T_g}{\omega_g^2}\right) \tag{9}$$

Essentially, *FI* tracks the change of K with respect to time. It is possible for the K to change in case of a WT as the fault related momentary change of the generator shaft speed causes to break up the linear relationship between T_g and ω_g^2 for that time instance. Therefore, *FI* would be an efficient fault detector as it only responds to the fault related disturbance of the generator shaft speed. Simulation experiment of a drivetrain fault has been carried out to evaluate performance of *FI*, which is presented in the result section.

3 Wind Turbine Model

The wind turbine model used in this paper, can be found in [14], which represents a realistic generic three-bladed pitch-controlled variable-speed wind turbine with a nominal power of 4.8 MW. It consists of four parts (Fig. 3), the blade and pitch system, drivetrain including gearbox, combined generator-converter model, and WT controller. The benchmark model describes the operation of a wind turbine at a system level with simplified model of converter and pitch system, rigid blades and tower, and a static model for WT aerodynamics. The WT controller, used in the model, performs the task of following the power reference (P_{ref}). In case of low wind speed the controller tries to optimize the power generation by tracking the MPPs using torque control method. At high wind speed the controller changes the pitch (β) of turbine blades to maintain nominal rotor speed while producing rated power. A more detailed description of different components of the benchmark model as well as their operation can be found in [14]. This benchmark model also

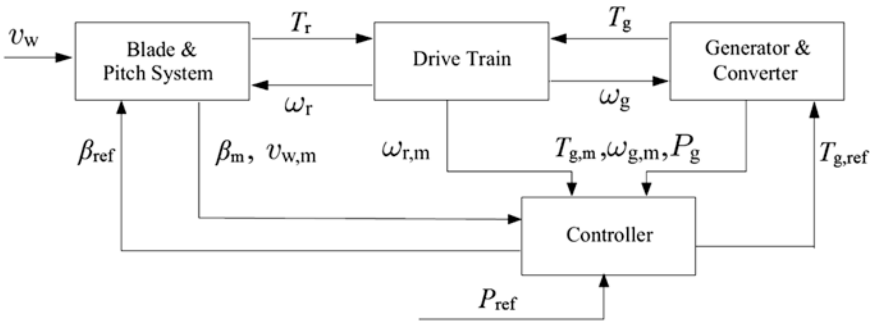

Fig. 3 Representation of a 4.8 MW wind turbine benchmark model ('m' in the subscript refers to measured quantity) [14]

provides the opportunity to observe the behaviour of a WT in case of several system faults along with normal operating performance.

As mentioned earlier, the WT benchmark model has a gearbox with gear ratio N_g in its drivetrain. Let us consider, the gearbox consists of a planetary stage and a parallel stage with gear ratio of N_{g1} and N_{g2} respectively. Here,

$$N_g = N_{g1} \times N_{g2} \tag{10}$$

In this work, gearbox fault is introduced in the drivetrain of the benchmark model as a representative of the drivetrain fault. A subsequent study has been carried out to investigate how *FI* responses to the normal as well as fault condition.

3.1 Gearbox Fault Model

The gearbox fault is realized by the tooth breakage in the gear attached to the generator driving shaft. In fact, while the gearbox is in operation, a broken tooth causes a gap between teeth of the two mating gear (Fig. 4), which in turn, translates mechanically to a transient variation of the shaft angular speed beyond that of other tooth-tooth contact [15]. As the generator shaft torque has a relationship with the gear speed through other system components and characteristics, an effect of the gear fault is expected on the torque signal also. In the referred WT model, the only input from drivetrain to generator is the shaft angular speed (ω_g). Therefore, kinematic error in gears, caused by the tooth breakage, is realized here as a disturbance in ω_g. This disturbance, named hereafter as angular speed error $\Delta\omega_g$, is determined based on the following assumption.

$$t_p \propto d_{th} \tag{11}$$

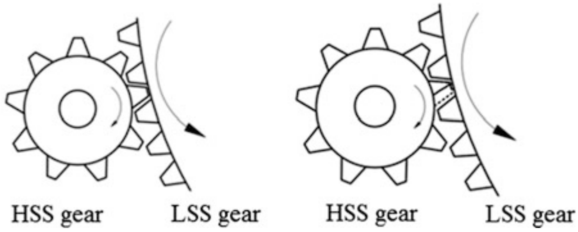

Fig. 4 Healthy gear set (*left*) and faulty gear set with tooth breakage (*right*) (*HSS* high speed shaft, *LSS* low speed shaft) [15]

where t_p corresponds to the time required for passing a tooth by the mating gear whereas d_{th} corresponds to the circular tooth thickness. According to Eq. (11), in a gear system, the time required for passing a tooth is proportional to the circular thickness of the tooth. In this work, gear fault is introduced in the generator shaft gear as a uniform reduction of d_{th}.

Let us consider that, the parallel stage has a low speed and high speed shaft, with respectively, n_l and n_h number of teeth. To simulate fault situation, one of the teeth of the high speed shaft, mentioned earlier as generator shaft, is assumed to have a reduced tooth thickness of d'_{th}. Therefore, reduction of circular thickness, in percentage, can be considered as the size of gear tooth defect which is regarded as d_s.

$$d_s = \frac{d_{th} - d'_{th}}{d_{th}} \times 100\ \% \tag{12}$$

If the time required for passing healthy and faulty tooth are t_p and t'_p, respectively, then from Eqs. (11) and (12) it can be written that,

$$t'_p = (1 - 0.01 \cdot d_s) \times t_p \tag{13}$$

Again, t_p can be expressed in terms of n_h and corresponding shaft speed ω_g.

$$t_p = \frac{2\pi}{n_h \cdot \omega_g} \tag{14}$$

Now, the angular speed error $\Delta\omega_g$, caused by the faulty tooth can be calculated by using Eqs. (13) and (14) as,

$$\Delta\omega_g = \left(\frac{1}{1 - 0.01 \cdot d_s} - 1\right) \times \omega_g = \frac{d_s \cdot \omega_g}{(100 - d_s)} \tag{15}$$

To simulate gearbox fault, $\Delta\omega_g$ is introduced in the shaft speed signal when a faulty tooth appears to its mating gear.

4 Simulation Results and Discussion

The simulation experiments have been carried out in MATLAB Simulink environment utilizing the WT benchmark model available in [16]. Properties of all the model parameters can be found in [14]. It should be mentioned here that, instead of using the fault scenarios presented in [14], only the drivetrain gearbox fault has been studied in this work following the above mentioned gearbox fault model. Properties of the gearbox related parameters are listed in Table 1.

For the simulation experiments, a predefined wind speed sequence is used which consists of real measurements from a wind farm. More details about the wind data can be found in [14]. Simulation has been performed to evaluate effectiveness of the proposed condition monitoring criterion *FI* in case of detecting fault at varying wind speed as well as measuring defect severity. The simulation results are shown in Figs. 5 and 6, for two different wind sequences each of 200 s length. The major WT operation related parameters along with the condition monitoring criteria are also included in the illustration. In the first case (Fig. 5) wind data varied between moderate and low speed which is apparent in the WT power output (Fig. 5b). In this case, WT controller controls generator torque to run it at maximum power points, therefore, generator speed is also varied. During some portion of these simulations the generator shaft gear is considered to have a defective tooth with a defect size of 0.1 %. The fault and normal situation is represented in the figure by the fault marker. The low value of fault marker represents a defect in the gear tooth, whereas, a high value corresponds to normal condition. As seen from Fig. 5e the condition monitoring criterion *C* shows a varying value during the WT operation from which no clear indication of fault occurrence can be obtained. The shape of *C*, as expected from Eq. (8), resembles generator speed signal. In contrast, the condition monitoring criterion *FI*, as proposed in this work, can efficiently indicate the abnormal situation (Fig. 5f). For normal situation *FI* takes the values around zero, as the relationship in Eq. (7) holds well. At the time of fault occurrence, *FI* responses to the change of relationship between generator torque and speed, that is reflected in its shape. The varying value of *FI* thus determines an abnormality in the drivetrain operating behaviour. Another useful feature of *FI* signal, during a fault situation, is the consistency in its shape irrespective of the speed variation. From Fig. 5f it can be easily noticed that, amplitude of the *FI* remains between −15 and +15 although the generator speed is not constant during this time.

For further investigation on the *FI* performance during nearly constant generator speed, Fig. 6 illustrates a situation where the wind speed is mostly above the WT rated speed. As a result, pitch controller takes over control of the WT and tries to maintain generator speed at the rated level (Fig. 6c) by changing pitch of turbine

Table 1 Properties of gearbox model parameters

N_{g1}	N_{g2}	n_l	n_h	No. of faulty tooth in HSS gear	Range of defect size (d_s)
7.6	12.5	100	8	1	0.1–1 %

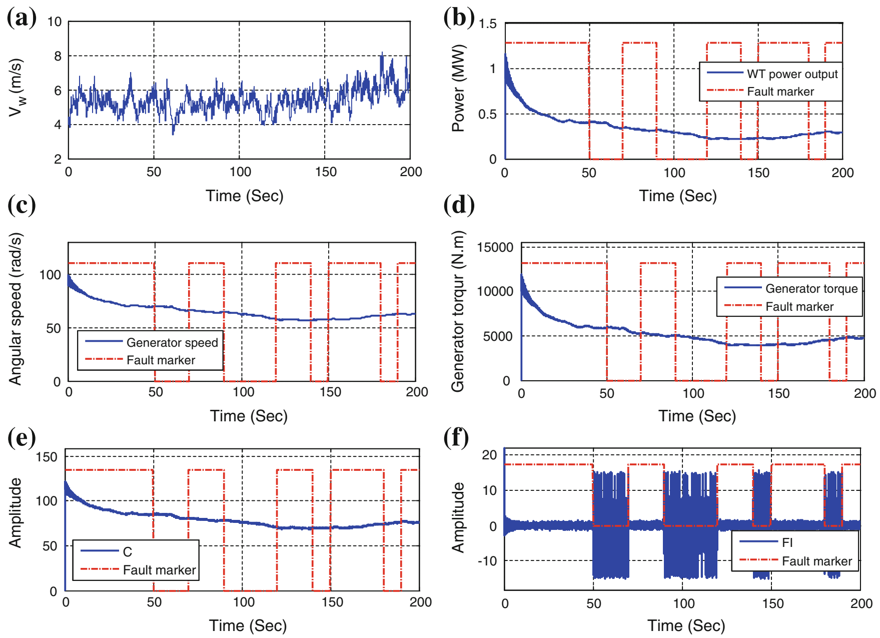

Fig. 5 Simulation results for low and moderate wind speed while d_s = 0.1 %; **a** wind speed, **b** power output of wind turbine, **c** generator speed, **d** generator torque, **e** condition monitoring criterion *C*, **f** proposed condition monitoring criterion *FI*

blades. As a result, power output of the wind turbine is nearly constant at the rated level as shown in Fig. 6b. Response of criterion *C* (Fig. 6e), again, shows similarity with generator speed, thus makes the fault and normal situation undistinguishable. On contrary, the *FI* signal shows distinct responses in case of normal and fault condition as shown in Fig. 6f. At the gear fault instances, again, amplitude of *FI* stays between −15 and +15.

For a more comprehensive investigation on *FI* response to gear fault at different wind speed, simulation has been performed for 11 different wind data sequences each of 200 s length at a fixed gear defect level of 0.1 %. In this analysis, to quantify fault sensitivity of *FI*, fault irrelevant peaks are first eliminated from *FI* signal by using appropriate threshold. Then severity index (*SI*) is determined according to the following equation.

$$SI = \frac{\sum_{i=1}^{N} |A_p(i)|}{N} \tag{16}$$

here, $A_p(i)$ corresponds to a peak in the processed *FI* signal and *N* is the total number of peaks found.

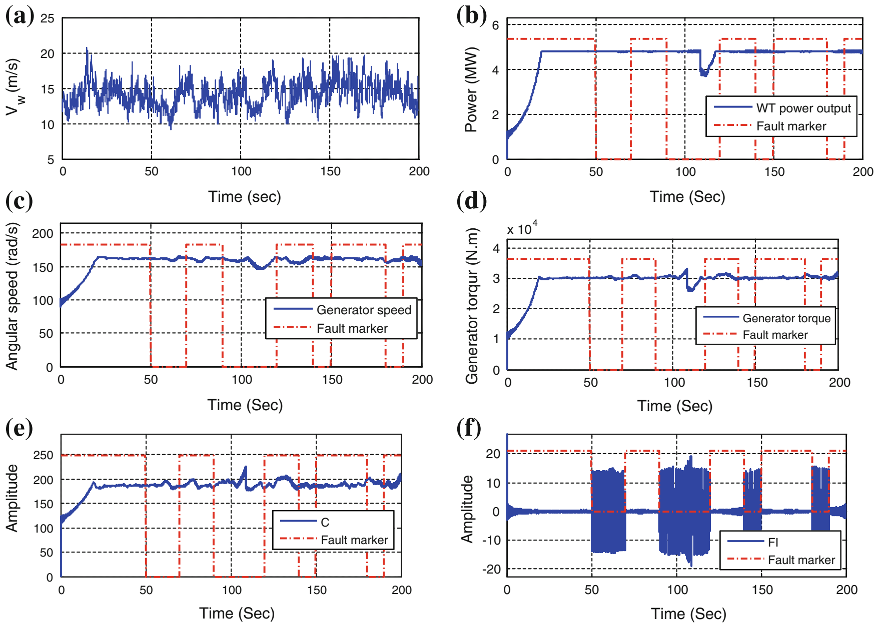

Fig. 6 Simulation results for high wind speed while $d_s = 0.1$ %; **a** wind speed, **b** power output of wind turbine, **c** generator speed, **d** generator torque, **e** condition monitoring criterion *C*, **f** proposed condition monitoring criterion *FI*

A plot of severity indices for the 11 different cases is shown in Fig. 7. An approximately constant value of *SI* is obtained for most of the cases which represents robustness of the criterion *FI* against wind speed variation. From Fig. 7 another characteristic of *FI* can be obtained, that is, value of severity index can be a representative of defect size of the gear tooth. Further investigation has been done to confirm this issue where the simulation was performed for different gear defect size using the same wind data sequence. The result is shown in Fig. 8 which represents the values of *SI* for defect size ranging from 0.1 to 1 %. A linear

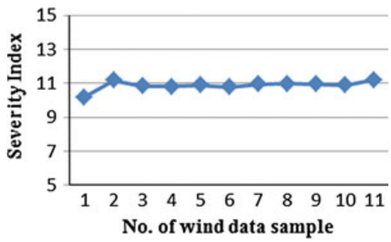

Fig. 7 Plot of severity index (*SI*) for different wind data sequences while $d_s = 0.1$ %

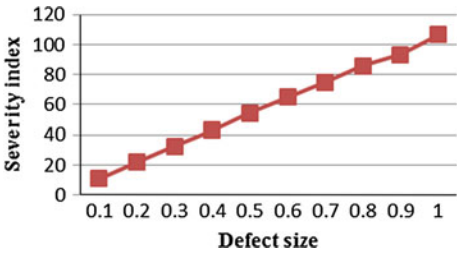

Fig. 8 Plot of severity index (*SI*) for different defect sizes (d_s = 0.1–1 %) of the gear tooth

relationship between the severity index and defect size is evident from this illustration. Therefore, *SI*, determined from the *FI* signal can efficiently measure the level of defect occurred in the drivetrain gear.

5 Conclusions

In this work, a novel condition monitoring criterion, named as fault indicator, has been proposed which is capable of detecting abnormality in the WT drivetrain while exhibiting robustness against the variable speed turbine operation. The level of defect can also be diagnosed by a severity index, calculated from the fault indicator. A benchmark WT model with a gear tooth fault is simulated to evaluate performance of the proposed criterion. Obtained results ensure its effectiveness at distinguishing normal and fault condition in the gearbox, which is not affected by the wind speed. In addition, the severity index shows a linear response to gear tooth defect size thus enables identification of fault severity level. Performance evaluation of the proposed fault indicator in case of other drivetrain faults like bearing fault and unbalance is under study. Note that, laboratory experiments will be performed in a near future by using a practical WT drivetrain to demonstrate feasibility of fault detection using the proposed criterion.

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Maintenance Method Based on Risk Estimation for 170 kV Pneumatic Type Gas Insulated Switchgear

Y.M. Kim, J.R. Jung, C.H. Kim and M.J. Jin

Abstract The number of 170 kV type gas insulated switchgear are 7,700 units, taking 28 % of total GISs operating in Korea. We identify and classify functional failures of sub-systems using failure mode and effect analysis and performed risk analysis based on the collected historical data for failures and surveys of experts. From the results, we selected the main sub-system and made a list of the priority of components by analyzing the components of the selected sub-system. Based on analysis of historical data for failures of the selected components, this paper proposes the checkpoints of each component and how to inspect components.

Keywords Risk assessment · Failure modes analysis · Maintenance management

1 Introduction

About 60 years ago, GISs were introduced to the market of electric power facilities in the world. About 80,000 bays are operated now and the number increases by 6,000 bays per year [1]. In Korea, 790 substations with 23 kV or higher are operated by the Korea Electric Power Corporation; 154 kV substations are 86 % and 345 kV substations are 13 % of them. The number of 170 kV GISs operating in Korea is more than 7,700, taking 28 % of total GISs.

However, as shown in Fig. 1, more than 30 % of 170 kV GISs have been operated for at least 15 years and 47 % of the failures for 13 years is from the GISs older than 10 years [3]. For the GISs, a maintenance method more effective than the traditional Time Based Maintenance (TBM), which has been used for most of electric power equipment maintenance, is required.

In this study, for pneumatic type GISs which show the largest degraded units of the 170 kV GISs in Korea, We defined classification and functional failures of

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_13

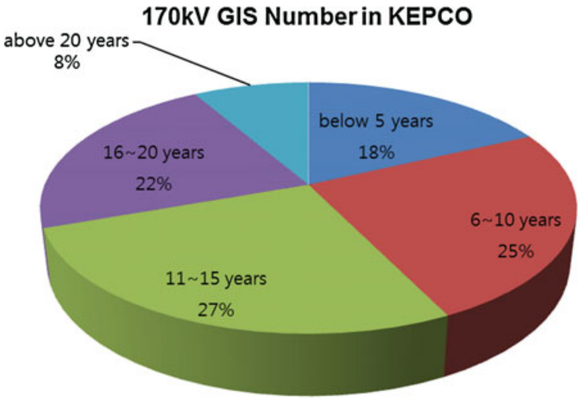

Fig. 1 Number of 170 kV by operating year

sub-systems using Failure Mode and Effect Analysis (FMEA) and performed risk analysis based on the collected historical data for failures and surveys of experts.

From the results, we selected the main sub-system and made a list of the priority of components by analyzing the components of the selected sub-system. Based on analysis of historical data for failures of the selected components, this paper proposes the checkpoints of each component and how to inspect components.

2 Configuration of Pneumatic GIS

A GIS is one of the electric power devices (equipment) which can reduce the installation space by 10–20 % comparing to the existing Air Insulated Switchgears (AISs); the components of the existing AIS substations (LA, CT, PT, CB, DS, ES, etc.) are configured in the metal enclosure filled with the high-insulating SF6 gas. In addition, it provides good earthquake-proof and operator's safety. The most typical GISs type operates the circuit breaker by using the operating force of the hydraulic, pneumatic, and spring types. In Korea, the pneumatic GISs are popular because they use compressed air (15 kg/cm^{2}G) for powerful operating force and are easily applied to the other device types by changing the pneumatic cylinder only. However, there are a lot of rust caused by condensed water on the pneumatic drive head and a lot of parts exposed to the external, causing operation delays and failures due to foreign materials. The pneumatic GIS are configured as shown in Fig. 2.

a. Switching components (circuit breaker, disconnectors and earthing switches)
b. Mechanical drive head (trip/closing coil, solenoid valve, various pneumatic valves, operation link, closing spring, dash-port, etc.)
c. SF6 gas, bushing and various epoxy resin insulations
d. Control/auxiliary circuits
   (current transformer, voltage transformer, and local control panel).

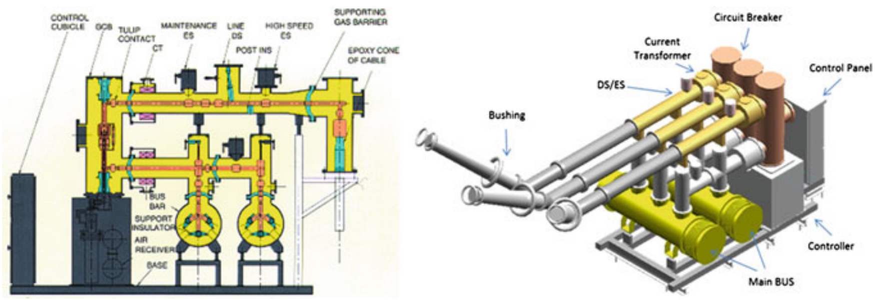

Fig. 2 170 kV pneumatic GIS configuration

3 Failure Modes and Effects Analysis

To evaluate the risk of pneumatic GIS components, FMEA is used [2]. The following FMEA procedure has been used for this study.

a. Classification of sub-systems
b. Functional failures and risks definition of sub-systems
c. Risk evaluation of sub-systems
   (Analysis of frequency/importance/detectiveness)
d. Selection of important sub-systems and analysis of the components
e. Risk evaluation of important components
   (Analysis of frequency/importance/detectiveness)
f. Selection of important components

3.1 Classification of Sub-systems and Definition of Functional Failures

We classified the sub-systems of the system (GIS) and defined the functional failure mode as shown in Table 1.

3.2 Analysis of Failure Data

We selected historical failure data related to pneumatic GISs among the 1,000 GIS failure data collected from utilities in Korea and classified the data into functional failures, sub-systems, and components by failure history.

Table 1 Example of functional failure classification

System	Sub-system	Function	Functional failure
GIS	Circuit breaker	Disconnect fault current	Not/bad breaking operation (A)
			Not/bad making operation (B)
		Open/close operation	Breaking operation without control signal (C)
			Making operation without control signal (D)
		Insulation	Insulation breakdown (E) etc.
	Disconnector	Charged current disconnect	Not/bad opening operation (A1)
		Loop current disconnect	Not/bad closing operation (B1)
		Insulation	Insulation breakdown (C1) etc.
	Earthing switch	Connect live parts to ground	Not/bad opening operation (A2)
			Not/bad closing operation (B2)
		Insulation	Insulation breakdown (C2) etc.
	Conductor	Current distribution	Disconnection (A3)
		Connect main bus	Connection status bad (partial discharge) (B3) etc.
	Enclosure	Internal protection	SF6 gas leak (A4)
		Airtight	Flashover (B4)
		Capacity to resist pressure	Breakage (aging, wear and corrosion) (C4)
		Insulation	Insulation breakdown (C4) etc.
	Panel/meters	Control	Control/signal cable disconnection (A5)
		Monitoring	Wrong signal generation (A5) etc.
		Operation	
	Lightning arrestor	Protection from overvoltage	Insulation breakdown (A6) etc.

3.3 *Definition of Risks*

The risks of GIS are defined as shown in Formula 1; the definition of frequency, importance and detectiveness of each risk is as follows.

$$\text{Risk} = \text{Frequency} \times \text{Importance} \times \text{Detectiveness} \quad (1)$$

a. Frequency: Estimated by classifying the functional failures of field data by sub-system level and counting the failures directly connected to accidents.
b. Importance: Estimated based on the system repair costs, loss of production for the time taken to restart electric power supply, damage for human and environmental pollution caused by the accidents.

c. Detectiveness: Estimated based on the method to detect abnormalities of sub-systems before accidents occur, possibility to cause accidents and emergency response time.

3.4 Analysis of Frequency/Importance/Detectiveness

Frequency has been estimated by classifying the failure types on the same GIS to the functional failure based on the field failure history data collected from the utilities in Korea. Table 2 shows the example of estimating frequency of the functional failure of the circuit breaker.

For Importance and Detectiveness, we scored each functional failure through surveys for the expert group of GIS manufacturers. Importance was estimated by using the AHP (Analytic Hierarchy Process) method from the aspects of repair costs, recovery time, damage for human and environmental pollution. Detectiveness was estimated from the aspects of detection method, possibility of causing an accident and response time. Table 3 shows an example of survey.

3.5 Important Sub-systems and Estimation of Risks

We estimated the risks based on the Frequency/Importance/Detectiveness of each sub-system. The Frequency/Importance/Detectiveness are weighted by using the AHP and Table 4 shows the result. The result of estimated risks is compared by normalizing the largest sub-system as a reference; the circuit breaker was ranked as the highest.

Table 2 Example of estimating frequency of circuit breaker

Sub-system	Function	Functional failure	Incidence rate (%)
Circuit breaker	Breaking/trip	A	37.2
		B	4.7
		C	0.0
		D	0.0
		E	0.0
		F	19.8
		G	0.0
		H	33.7
	Conducting	I	4.7

Table 3 Example of survey of importance/detectiveness

Question item	Answer items
What method to detect failure sign before failure?	Condition diagnosis, periodic inspection, overhaul, no
When a failure is detected, what is the response to an emergency?	Visual inspection, utility own actions, manufacture A/S
After performing the emergency response, the possibility of actual breakdown occurs how many?	Below 50 %, excess 50 %
How much failure can actually occurred?	No history of occurrence, 1–10 cases/decade, 11–20 cases/decade, above 20 cases/decade
What kind of damage that occurs there when occur failure?	Repair costs, blackout, casualties, pollution
When failure occurs due to repair, what is the scope of the repair cost?	100 million won<, 50 million won–100 million, below 10 million
When a power outage occurs, what is the recovery time?	1 week<, 1 week>, 1 h>, several minutes>
The damage occurs when people get hurt, what is the scope of the damage?	Dying, serious wound, wound, threat
When pollution occurs, what is the scope of the damage?	SF6 gas large spill, SF6 gas small amount spill

Table 4 Selecting important sub-system

Sub-system	Risk (%)	Ranking
Circuit breaker	100.0	1
Disconnector	6.8	7
Earthing switch	13.4	5
Conduct	25.5	3
Enclosure	8.8	6
Panel/cable	92.2	2
etc.	16.2	4

3.6 Classification of Components and Selection of Important Component

Table 5 shows classification of components of the circuit breaker selected as an important sub-system. It is categorized to four: Circuit Breakers, operating part, pneumatic supply, and other part, and classified into 25 components for analysis.

The components and failure history data were re-classified into Functional Failure A–I of the circuit breaker to estimate the risk. Table 6 shows the risk score of Functional Failure A–I for each component. The score of each component are normalized by functional failure for comparison. The risk of components of the circuit breaker was high in the order of solenoid valve, shield, and main valve.

Table 5 Classification of components

Sub-system	Component level 1	Component level 2
CB	Breaking/making part	Insulation support
		Insulation rod
		Arc contact
		Main contact
		Nozzles
		Puffer cylinder
		Shield
		Tulip contact
		Conductor
	Mechanical drave part	Operating cylinder
		Main valve
		Solenoid valve
		Closing hook
		Closing spring
		Dashpot
		Operating link
		Silencer
		Aux contact, cable
		Air tank
	Pneumatic supply part	Air compressor
		Air piping
		Air valves
	etc.	Indicator
		Heater
		Cases

Table 6 Example of estimating risk by component

	A (%)	B (%)	C (%)	D (%)	E (%)	F (%)	⋯	I (%)	Rank
Nozzles	0.3	1.6	5.6	5.6	20.2	0.6	–	1.7	10
Puffer cylinder	0.3	1.6	5.6	5.6	20.2	3.8	–	9.4	8
Shield	0.3	1.6	5.6	5.6	3.5	66.1	–	1.7	2
Tulip contact	0.1	0.6	2.0	2.1	1.3	0.6	–	9.3	16
Conductor	0.3	1.6	5.6	5.6	3.5	2.9	–	13.1	11
Operating cylinder	3.1	5.1	5.6	5.6	3.5	0.6	–	1.7	9
Main valve	35.3	1.6	5.6	5.6	3.5	0.6	–	1.7	3
Solenoid valve	40.0	1.1	21.4	3.8	2.4	0.4	–	1.1	1
⋮	–	–	–	–	–	–	–	–	–
Air tank	2.4	1.1	3.8	3.8	2.4	0.4	–	1.1	14
Air compressor	4.8	0.1	0.3	0.3	0.2	0.0	–	0.1	18
Air piping	0.7	0.1	0.3	0.3	0.2	0.0	–	0.1	21
Air valves	0.3	0.1	0.3	0.3	0.2	0.0	–	0.1	22
etc.	0.1	0.1	0.3	0.3	0.2	0.0	–	0.1	23

4 Conclusion

In this study, we selected the sub-system with the highest risk (circuit breaker) by using the FMEA method for the pneumatic GIS which uses the pneumatic operating force, classified the components of the selected sub-system and selected the important components (main valve, solenoid valve and shield) based on the risk analysis. We hope it can be used as a reliable maintenance method for electric power devices which can complement the traditional TBM maintenance. Later, additional studies for important components of all sub-systems of GIS will follow.

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No Fault Found and Air Safety

Christopher J. Hockley and Laura Lacey

Abstract There is a view that has been expressed in some organizations that No Fault Found (NFF) is not an air safety issue. Consequently the occurrence of NFF and the rates for a particular fleet do not get the attention that they deserve in these organizations. In this paper it is shown that there is a distinct similarity between maintenance errors that could cause accidents and NFF causes and their impact on air safety. It is concluded that NFF needs a higher profile and the acknowledgement that it certainly ***is*** an air safety issue.

1 What is NFF?

In considering whether NFF is an air safety issue it must first be established what is meant by NFF. In simple terms when a fault occurs and the cause cannot be found or reproduced when the diagnosis is carried out, the system is then tested and passed serviceable; this is a NFF but often is not recorded as such. Subsequently, however, the same fault may re-occur in the next or a subsequent mission. Individual items, components and Line Replaceable Units (LRUs) may then be removed as part of the diagnosis and replaced with a known serviceable item and the system tested satisfactorily; however, now a NFF may occur when the item is tested further down the support chain at another maintenance facility and no fault is apparent. All these instances incur costs of one sort or another, such as the nugatory maintenance performed with no fault confirmed or with transport, handling costs and associated manhour costs throughout the support chain. This drives up the cost

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_14

of Through-life Engineering Services and Support and solutions must be found if these damaging in-service costs are to be reduced throughout an equipment's life.

There are many and varied causes for NFF ranging from organizational, procedural, process and even behavioural issues, to the more obvious original design faults that do not cope with the current operational conditions and changes in usage from the original design requirements. These are just some of the situations that contribute to NFF and the costs can be huge. The onus for solutions though surely lies with engineers and the maintenance organizations yet the acknowledgement of the true costs of NFF is often sadly lacking.

2 The Maintenance Contribution

What is Maintenance? We are all familiar with the concept of maintenance and understand that it is all about inspecting and servicing equipment to ensure it is able to be put back into service in a fit condition to last until the next maintenance intervention. Most people also associate maintenance with finding failures and repairing them. Indeed definitions in the air environment indicate that there is a very necessary and vital flight safety link with maintenance and the need for it to be undertaken; definitions will cite the need for maintenance to ensure or restore *aircraft integrity*. Consequently the view expressed by Jack Hessberg[1] should certainly be accepted which is that maintenance is therefore "nothing more than the management of failures" [1].

It is important to note of course that the management of failures is driven by the consequences of the occurrence of failures. These are:

- The impact on safety
- The impact on operational availability

Both are vital and the impact on safety receives huge attention and rightly so. The impact on availability however, receives more attention in commercial aviation where delay and cancellations cost money and reputation and ultimately affects shareholders and profits. In military aviation it is, however, beginning to receive more attention as resources and numbers of aircraft are reduced and more commercial ways are found to provide support and availability. Yet the whole process of the management of failures and the need for maintenance is different between military aircraft and civilian aircraft. Whilst both will consider the impact on safety in the same way, the impact on availability will be largely economic for the airline industry but in the military will be driven by the need for a battle-winning edge. This also produces subtly different cultures and behaviours between these two groups. The need to achieve dispatch reliability for an airline will be

[1] Jack Hessberg (1934–2013) was Boeing Chief Mechanic with responsibility for all maintenance design during development of the Boeing 777.

paramount as the economic consequences of delays, or worse, cancellations, can be very damaging. Consequently, the maintenance staff will do almost anything to achieve the minimum delay when faced with a failure "at the gate." The culture in many airlines is one that minimizes delays at the gate and if this means changing three boxes rather than carrying out thorough diagnostics to find the root cause of the failure and the exact box at fault, then three boxes will be changed. In peace-time operations this culture in the military would be unusual and particularly now when so many civilian companies are providing the maintenance support to the military. However, in actual operations, where battle-winning availability is vital, then the same culture may well pervade.

A second factor—aviation safety—is also at play here. Civilian airliners are built to fail-safe principles where every system and part of the design is meticulously analysed for the consequences of it failing. Should that be a possibility, there must be an alternative load-path or alternate system to provide redundancy. Military aircraft, however, are built to safe-life principles where maintenance is a key factor in providing the early warning of failure before it is catastrophic [2].

Regardless of whether fail-safe or safe-life though, various maintenance techniques are increasingly used and incorporated into the design of both military and civilian aircraft to provide maintenance assistance. Condition monitoring in its widest sense in commercial aircraft such as the Boeing 777, uses a huge amount of condition monitoring of all forms to monitor the deterioration of systems and components. The information is collected by the Aircraft Integrity Management System (AIMS). By identifying faults through the condition and health monitoring, AIMS will reconfigure systems or divert usage to other systems using spare capacity or redundancy so that the need for urgent maintenance is avoided and postponed. The AIMS also continually monitors the systems and sends information to the maintenance staff to enable them to analyse the data and information to determine both impending and actual faults and failures. The necessary maintenance can then be planned at a convenient time for maintenance staff who can be warned and positioned with the right skills, the right test equipment, the right spares and within the most appropriate servicing window. Built in Test (BIT) and Built in Test Equipment (BITE) are part of the whole AIMS system and contribute to this management of failures or impending failures.

2.1 Operational Pressure

The pressure in commercial operations on maintenance staff is often overwhelming. Aircraft delays, cancellations and lack of aircraft availability not only mean lost revenue but have a knock-on effect in customer perception. Reputation is hard won but all too easily lost if delays or cancellations occur. Delays and cancellations between 2003–2013 for US domestic carriers averaged more than 21 % [3]. Whilst some of these are due to uncontrollable issues such as weather or air traffic controls, a great many are because of faults or maintenance delays.[2] The pressure on maintenance staff then becomes extreme, yet safety is still paramount. In that case the easiest solution to a fault or failure will be taken, perhaps without time for proper diagnosis. If the system can be reset and tests satisfactorily, the fault is no longer present! Yet it may need vibration, temperature or humidity whilst airborne to provide the conditions when it will fail again. Operational pressure might also suggest that changing three boxes will solve the failure and so it does, but now two of the boxes will prove to be NFF when tested further down the support chain. In some cases, speed and operational imperatives will have masked the failure which may then re-occur at an inappropriate moment during the next flight. The integrity of maintenance staff is all that stands in the way of whether a fault or failure is solved in the most effective way. There will surely be some occasions when speed and operational pressure win and a dormant fault remains on the aircraft, or in the removed component. The operational pressure is created of course by the organization and the humans who manage the organization. There are also human factors at work within the maintenance organization which relies on the maintenance personnel to undertake work and these human factors must also be understood.

3 The Human Factors Contribution

When humans are involved, errors can occur for any number of reasons. The Civil Aviation Authority (CAA) goes further stating:

> It is an unequivocal fact that whenever men and women are involved in an activity, human error will occur at some point (CAA [4])

Reference [5] in a paper on the taxonomy that delivers dependability, albeit associated with computing, shows how dependability is made up of three elements: attributes, the means (of delivering dependability) and threats. The attributes are availability, reliability, safety, confidentiality, integrity and maintainability; the means by which dependability can be delivered are fault tolerance, fault prevention, fault forecasting and fault removal; the threats are faults, errors and failures Ref. [5]. Whilst the paper concerns dependability of computers and computer systems, the concept of dependability is equally valid for any engineering system or service

[2] The U.S. Department of Transportation's (DOT) Bureau of Transportation Statistics (BTS) tracks the on-time performance of domestic flights operated by large air carriers. Summary information is provided on the number of on-time, delayed and cancelled flights—On time 78.02 %, Delay—20.03 %, Cancellation—1.72 % between June 03 and Oct 13. For purposes of this report, a flight is considered delayed if it arrived at (or departed) the gate 15 min or more after the scheduled arrival (departure) time as reflected in the Computerized Reservation System. The information is based on data submitted by reporting carriers which number between 14 and 19 over the period.

delivery. In the context of understanding the contribution of NFF to air safety, it is important to distinguish therefore between faults, errors and failures and the definitions and taxonomy given by Avizienis et al. [5], is as good as any. In sum, they propose that failure means that a system deviates from the correct service state and fails to deliver the required service. The deviation is called an error. The adjudged or hypothesized cause of an error is called a fault [5]. On the other hand in his acclaimed book “Human Error”, Professor James Reason defines error as follows:

> Error will be taken as a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency. Reason [6]

So when considering maintenance and the resolution of faults and failures, errors must be considered as well; however in the context of this paper it is not the error in the physical system that is of concern, but rather the maintenance errors associated with the humans performing the maintenance itself.

There are costs associated with maintenance errors; firstly maintenance errors cost lives and secondly maintenance errors cost money. Maintenance errors also cost a Company its reputation though. In fact errors merely keep lawyers in business and ultimately generate more and more regulations. Maintenance errors can be thought of as resulting from what James Reason describes as “The Error Chain” [6]. Simple errors often combine to create a catastrophe; by themselves they would not be a problem but the combination becomes serious. The Error Chain can cost a Company millions in rework and lost revenue and invites unwelcome attention from regulators. Examples of errors are:

- Incorrect installation of components.
- Fitting the wrong part.
- Electrical wiring discrepancies.
- Loose objects left.
- Inadequate lubrication.
- Access panels, fairings or cowlings not secured.
- Fuel or oil caps not secured.
- Safety or gear pins not removed before aircraft departure.

Maintenance technicians work in a variety of environments, often extremely challenging ones, to deliver the outputs that are required. The performance of those maintenance tasks is affected and interfered with by many things, yet the technician will be coping by using both conscious and sub-conscious approaches to deliver the desired performance. The sub-conscious will be delivered as automatic or emotional actions, whereas the conscious approach will be delivered with logical and rational activities. The conscious actions include activities delivered according to rules and procedures, or based on experience, knowledge and training. The maintenance activities delivered with a sub-conscious approach will include those activities done automatically without thinking and could involve fast reaction and perhaps repetitive activities. Maintenance errors are usually obvious and can be traced to one or more causes which were identified and christened the “dirty dozen” by Dupont [7], as a concept developed whilst he was working for Transport Canada; the dirty dozen forms part of an elementary training programme for understanding Human Performance in Maintenance. The dirty dozen have since been expanded but essentially still forms the basis of the ways that degrade people’s ability to perform effectively and safely and which could thus lead to maintenance errors; they are well known in the commercial airline industry and feature prominently in maintenance training courses. They are:

- Stress
- Fatigue
- Lack of Communication
- Lack of Assertiveness
- Complacency
- Distraction
- Pressure
- Lack of Resources
- Lack of Knowledge
- Lack of Awareness
- Norms (where incorrect procedures or quick fixes become the normal way of working)
- Lack of Teamwork.

These are all human factors as they impact on the ability of maintenance personnel to perform effectively and safely. Any one of these factors, or a combination of them, can result in a maintenance error or the failure to detect a fault. It is this latter point that is often dismissed or not considered and where the connection with NFF can be critical in its impact on air safety. The inability to locate or find a fault does not usually have such an obvious cause and is usually not considered a maintenance error. Yet if the dirty dozen is considered in the context of fault finding and achieving diagnostic success, many of the dirty dozen will actually cause a NFF to be registered. Table 1 considers each of the dirty dozen and assesses whether each can contribute or even directly cause a NFF. There is an almost perfect fit and in that case indicating that NFF resolution must surely be given the same prominence as the Dirty Dozen!

It is clear therefore that the human factors of the dirty dozen that cause maintenance errors and possible safety issues or accidents, are also the same factors that can contribute to NFF. It is therefore logical to conclude that there is a strong link, a cause and effect even, to the fact that NFF is also an air safety issue.

Table 1 The dirty dozen and NFF

Dirty dozen factors	Contribute to, or cause NFF?	Comment
Stress	Yes	Stress affects concentration, motivation and clear thinking which are essential for successful diagnosis of complex faults
Fatigue	Yes	Fatigue hampers the ability to think clearly and successfully diagnose the cause of a fault
Lack of communication	Yes	With rushed or poor communication, poor briefing and description of fault symptoms can often lead to NFF being declared
Lack of assertiveness	Yes	When directed by supervisor to a specific course of action a technician who lacks assertiveness will fail to question the course of action he has been directed to follow which he knows to be incorrect; this may lead to a NFF
Complacency	Yes	The maintenance action carried out is to perform the usual fix and course of action and which may result in temporary fix of intermittent faults or connector faults but which does not get to the real root cause
Distraction	Possibly	The technician may miss crucial elements of diagnostic procedures due to distraction and thus not find the fault
Pressure	Yes	Pressure may involve changing three items in order to make sure the cause of the fault is covered. This subsequently creates a NFF further down the support chain
Lack of resources	Yes	Inadequate resources will hamper diagnosis e.g. unsuitable test equipment may be used or lesser skilled technicians tasked who do not have the capability to successfully diagnose the root cause
Lack of knowledge	Yes	Inadequate training will cause poor diagnosis and the need for checks and supervision will be missed
Lack of awareness	Possibly	Similar to lack or poor training and lack of experience to use the best diagnostic process
Norms (e.g. short cuts and unauthorised procedures	Yes	Some short cuts will have become the normal solution for some faults and will have become the preferred yet unauthorised first solution to be tried as it usually clears the fault
Lack of teamwork	Possibly	The inability of a team to work successfully together may result in a NFF as a way of shortening the maintenance time so that the team has the least time working together

4 Diagnostic Maintenance Success

Having made the link therefore with maintenance errors, it is worth looking at maintenance support and guidance. Where does the technician get help? In modern aircraft it is increasingly from the On-board Maintenance System (OMS) or the Aircraft Integrity Management System (AIMS). The OMS on the Boeing 777 provides direct computer access to many of the systems on the aircraft in order to start any maintenance action. It consists of a central maintenance computer that takes inputs from condition monitoring systems and BITE. There are direct access points for a maintenance engineer to plug in a terminal around the aircraft. However, BIT and BITE have their inherent problems. BIT and BITE have become central to the diagnosis of faults, yet they have their inherent and specific level of reliability built upon the ever increasing level of complexity of the systems they are monitoring. There are subtle relationships between systems that need to be understood by the designer of the BIT and BITE. More and more parameters can be monitored, from vibrations and pressures to avionic performance and even structural health and so the complexity and difficulty of producing reliable test routines continually increases. Unfortunately what is needed for success here is a logical method for effective fault consolidation. If BITE falsely identifies component failures that do not exist, components may be designated as faulty when they are not. Perhaps the fault has in fact been caused by another component that feeds data into the first one—an example of what is known as cascading faults. Complex digital circuits are extremely sensitive to power surges and transient voltages which cause the monitoring circuits to register a fault. When a reset or a test fails to reproduce the fault, a NFF is generated and the BIT/BITE starts to get a poor reputation for identifying spurious faults that cannot be reproduced. As aircraft design and the OMS has been developed, the danger for the maintenance organization is an overload of data. There can be in excess of 100 BITE messages describing the condition of one system such as the landing gear. Does this help the engineer with his diagnostics? Now he has too many options and may take the path of least resistance, especially if operational pressure demands that there is too little time to diagnose the fault more carefully. If the human factors contribution is added into the ever more complex problem of achieving maintenance diagnostic success, there is a huge potential for NFF to be recorded and an error chain to be created.

5 Summary and Case Study

It is clear that NFF is a serious problem to the airline industry in particular as it affects aircraft availability and causes delays and cancellations, all of which have a damaging effect to airline revenue and reputation. Airlines thus treat NFF in a number of ways; many will accept high NFF rates if their delays and cancellations are minimised, ensuring reputation and revenue is paramount; others may hide the issue or are having NFF issues without actually realising it and the cost to their business. There are many causes though of NFF and it has been shown that there is a huge similarity between the human factors that cause maintenance errors and those that cause or contribute to NFF. Yet maintenance errors, described as the “Dirty Dozen”, have received a great deal of publicity as they have been accepted as being the factors that contribute to maintenance errors that cause aircraft incidents and accidents. The link between NFF and aircraft safety is, however, yet to be fully understood and accepted. If there is such similarity between NFF causes and the causes and impact of maintenance errors, it is only time before an accident and loss of life can be directly linked to the occurrence of NFF. A recent Air Accident Investigation Board report makes a clear link between NFF and a potential near accident and is worthy of detailed study (AAIB Bulletin).

6 No Fault Found (NFF) Certainly *IS* an Air Safety Issue—A Case Study

Examples exist that would appear to have serious flight safety implications; one such example is faults with the Merlin helicopter and its radio in Afghanistan, where transmit/receive faults were often not obvious to the pilots but also could not be replicated on the ground. A recent Air Accident Investigation Bulletin (AAIB) reported an incident on the 11th Sept 2010 which very nearly led to a crash by a Dash-8 Q400 aircraft (G-JECF), [8] and is a particular case study worthy of study.

During approach the aircraft experienced a failure of the number 1 Input Output Processor (IOP 1). The flight crew became distracted with this failure and were unaware that the altitude select mode of the flight director had become disengaged and that the aircraft had descended below its cleared altitude. Descent continued until, alerted by an Enhanced Proximity Ground Warning System (EPGWS) alarm, the pilots climbed the aircraft and re-established the glidepath. The maintenance action following the incident recorded NFF with the relevant circuit breaker being reset and system tested satisfactorily. The aircraft was released for service with a request for further reports from the aircrew. The subsequent detailed AAIB investigation found that the IOP 1 failure was caused by intermittent electrical contact arising from cracked solder on two pins of a transformer on the IOP power supply module. This IOP fault happened on this aircraft no less than eight times between 22nd August and 8th October. In each case the fault had been recorded as NFF with various maintenance actions completed such as swapping with the number IOP 2. Indeed after the first swap on 20th Sep, it was then IOP 2 being recorded as faulty. Yet it was not then until the 8 Oct that the faulty serial numbered item was removed and replaced and sent to the Original Equipment Manufacturer (OEM), Thales, for investigation. It was established that extensive tests were needed by the OEM to finally reproduce the fault on this IOP that was subsequently proved to have an intermittent fault caused by cracks in the solder of some surface mounted components on one of the electronic boards. IOP failures were a common occurrence but were often tested satisfactorily on the ground or tested serviceable by resetting a circuit breaker or re-installing the processor.

Removals were not common due to the high rate of NFF with only 20 % of IOP failures being confirmed across the fleet. Even those returned to the OEM produced a number that were NFF. Consequently, the Company has instituted a procedure where serial numbers need to be tracked more carefully with linkage to reported faults. In order to reduce the risk further of IOP units with intermittent faults being declared serviceable and subsequently fitted to aircraft, the following Safety Recommendation was made:

Safety Recommendation 2012-019
It is recommended that Thales Aerospace review the Input Output Processor test procedures to improve the detection of intermittent failures of the ERACLE power supply module in order to reduce the number of faulty units being returned to service.

Hopefully, this particular NFF history has now been solved and will not contribute to an accident. How many other NFFs with other operators though are just waiting to contribute to an accident?

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Feature Extraction Based on Cyclic Adaptive Filter for Gearbox Fault Diagnosis

Guangming Dong, Jin Chen and Ying Ming

Abstract The feature extraction of gears and rolling element bearings under strong background noise are of great importance for the gearbox fault diagnosis. In this paper, a method based on cyclic adaptive filter is applied to gearbox fault diagnosis. Firstly, adaptive line enhancer is used for the periodical component extraction, and then the residual signal will be filtered by cyclic Wiener filter. Based on the proposed method, the condition of each parts of gearbox can be well monitored, and the transient fault feature can be effectively detected. The effectiveness of the method is demonstrated by simulation and experimental validation.

1 Introduction

As the vital parts of rotating machinery, gears and rolling element bearings play very important roles in the whole system. Especially in the vibration signals of gearbox, gears and rolling bearings signals have different properties and should therefore be analyzed with different statistical tools. Parameters of gears are periodic, which is considered as first-order cyclostationary [1–3]. While, parameters of rolling bearings are periodically time-varying, especially for those under failure situation, which implies second-order cyclostationarity [4–7].

Adaptive Line Enhancer (ALE) can be used to extract the periodic part from broadband components in terms of prediction theory [8–10]. In adaptive line enhancer, the expected response is chosen as time-lag of a segment of sampled data, which can be seen as past values of the input signal. The periodic component can be reliably predicted from its past values. The prediction of random component from past values becomes less and less accurate as the delay becomes large.

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_15

Cyclic Wiener filter exploits the spectral coherence theory induced by the second-order cyclostationary signal [11–13]. The cyclic frequencies of the analyzed signal are required as prior knowledge. The cyclic frequencies are used to frequency shift of the original signal. The noise component is optimally filtered by a filter-bank.

When fault occurs on the gearbox, we should first detect whether it occurs on gears or rolling bearings. In this study, adaptive line enhancer and cyclic Wiener filter are combined and applied to gearbox fault diagnosis. The original signal is inputted to ALE to extract the gear vibration components, and the residual signal is filtered by cyclic Wiener filter to obtain bearing vibration components. Then the envelope spectrum is calculated for further fault diagnosis.

This paper is organized as follows. Section 2 gives the mathematical model of gearbox fault. In Sect. 3, a method of gearbox fault diagnosis is proposed, and the performance analysis of the method is discussed. Section 4 illustrates the validity of the proposed method using simulated data. In Sect. 5 experimental data are analyzed. Section 6 gives the conclusion.

2 Vibration Mathematical Model of Gearbox Fault

Gears and rolling bearings are two of the vital parts in a gearbox. When faults occur on gears or bearings, the vibration signal of gearbox can be modeled as the summation of gear signals and bearing signals, viz:

$$x(t) = x_g(t) + x_b(t) + n(t) \tag{1}$$

The gearbox signal can be decomposed into components of gears $x_g(t)$, which present first-order cyclostationarity, components of bearings $x_b(t)$, which present second-order cyclostationarity and random stationary noise $n(t)$. The sketch map of gearbox signal decomposition is presented in Fig. 1.

First-order cyclostationary signal is that whose first-order moment or expected value $m_x(t)$ is periodic with period T:

$$m_x(t) \triangleq E\{x(t)\} = m_x(t+T) \tag{2}$$

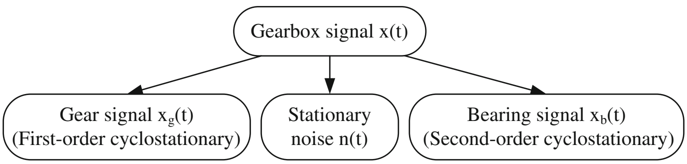

Fig. 1 Decomposition of gearbox signals

Second-order cyclostationary signal is that whose second-order moment or time-varying autocorrelation function $R_x(t,\tau)$ is periodic, and accepts a Fourier expansion

$$R_x(t,\tau) = E\left\{x\left(t+\frac{\tau}{2}\right)x^*\left(t-\frac{\tau}{2}\right)\right\} = \sum_{\alpha\in A} R_x^{\alpha}(\tau)e^{j2\pi\alpha t} \tag{3}$$

where the Fourier coefficient $R_x^{\alpha}(\tau)$ are non-identically zero over a countable set A of cyclic frequencies α (Gardner [14]).

The spectral correlation density function $S_x^{\alpha}(f)$ of $x(t)$ is the Fourier transform of $R_x^{\alpha}(\tau)$, viz:

$$S_x^{\alpha}(f) = \int_{-\infty}^{\infty} R_x^{\alpha}(\tau)e^{-j2\pi f\tau}d\tau \tag{4}$$

when a signal exhibits second-order cyclostationarity, its spectral correlation density function has non-zero values along lines parallel to the *f*-axis in the (f,α) plane (Gardner [15]).

In order to better understand the vibration characteristics of gearbox fault, it is necessary to know the mathematical models of gears and bearings first.

2.1 Vibration Mathematical Model of Gears

When fault occurs on gears, the vibration signal presents the feature of amplitude modulation and frequency modulation of the shaft rotational frequency [2]. The basic fault characteristic frequencies of gears are mesh frequencies and their harmonics modulated by the shaft rotational frequencies. The model of gear can be expressed as follows:

$$x_g(t) = \sum_m a_m(t)\cos[m2\pi f_z t + b_m(t) + \varphi_m] + n(t) \tag{5}$$

where f_z is the mesh frequency of gear. $n(t)$ is a white noise. $\mathrm{a}_m(t)$ and $\mathrm{b}_m(t)$ are the amplitude modulation function and frequency modulation of mth mesh frequency, respectively. $\mathrm{a}_m(t)$ and $\mathrm{b}_m(t)$ are periodic functions composed of the shaft rotational frequency and their harmonics, which can be expressed as

$$a_m(t) = \sum_n A_{m,n}\sin\left[n2\pi f_r t + \theta_{m,n}\right] \tag{6}$$

$$b_m(t) = \sum_n B_{m,n} \sin\left[n2\pi f_r t + \eta_{m,n}\right] \tag{7}$$

where f_r is the shaft rotational frequency of the failed gear.

2.2 Vibration Mathematical Model of Rolling Element Bearings

Mcfadden proposed a model produced by a single point defect [16]. And soon afterwards, the model was extended to describe multiple point defects [17]. In addition, [18] has modified the mathematical model of rolling element bearing as follows, considering the random slip of rolling elements and the cage, which has been successfully used [4, 5, 19]:

$$\begin{cases} x_b(t) = \sum_{i=1}^{M} A_i s(t - iT - \tau_i) + n(t) \\ A_i = A_0 \cos(2\pi Qt + \phi_A) + C_A \\ s(t) = e^{-Bt} \cdot \sin(2\pi f_n t + \phi_w) \end{cases} \tag{8}$$

where $s(t)$ is the oscillating waveform generated by a single impact. T is the average time between two adjacent impacts. A_i is the amplitude of the ith impact force. τ_i is the time lag from its mean period due to the presence of slip. $n(t)$ is an additive background noise. C_A is a constant ($C_A > A_0$). B is the damping coefficient of the system, and f_n is the natural frequency of the system.

3 A Method of Gearbox Fault Diagnosis

In the vibration signals of gearbox, gears and rolling bearings signals have different properties and should therefore be analyzed with different statistical tools. In this paper, Adaptive line enhancer (ALE) is used to extract the periodic part under broadband background noise. The residual signal is filtered by Cyclic Wiener filter to obtain second-order cyclostationary signal. Then power spectral density and envelope spectrum are calculated for further fault diagnosis. The processing method of gearbox signal with faults is illustrated in Fig. 2.

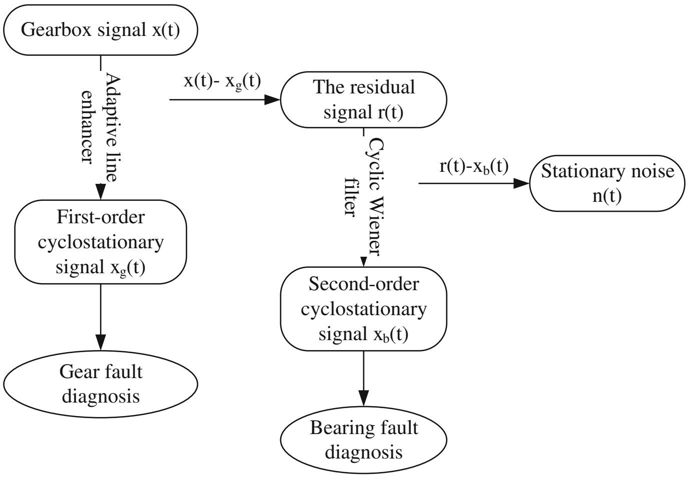

Fig. 2 Processing method of gearbox vibration signal with faults

3.1 Adaptive Line Enhancer (ALE)

The principle of ALE is based on processing the delayed input signal with a transversal filter and then subtracting it from the input signal to produce a prediction error. The weights of the transversal filter are adaptively adjusted to minimize the prediction error, as shown in Fig. 3.

Prediction theory gives an elegant solution for the separation of periodic signal from broadband signal. It was pointed out that the periodic signal could be predicted from its past values with zero prediction error. On the other hand, the prediction of broadband signal from past values becomes less and less accurate as time-lags become large. Ultimately, when the data used for prediction becomes older than the memory (effective correlation time) of the broadband signal, the best predicted value is zero and the prediction error equals the signal itself. This forms the basis of separation scheme, where the periodic signal is predicted from the remote past values of the vibration signal with zero prediction error.

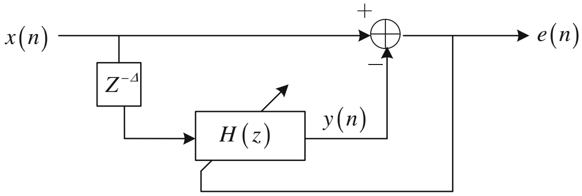

Fig. 3 Adaptive line enhancer

The time delay Δ (also called the prediction depth) should be chosen long enough so as to exceed the memory of the broadband components in the input signal, but not that of the periodic components. Since in theory the correlation time of a periodic signal is infinite, Δ could be set as large as possible. In practice, one is faced with two trade-offs. Firstly, the sampled signal is usually of finite length (off-line processing), and thus the choice of Δ determines the amount of data which can be processed. Secondly, the first-order cyclostationary signal may not be exactly periodic but rather pseudo-period—that is with a small distribution in its periodicity. In this case the time delay should not be set too large.

3.2 Cyclic Wiener Filter

The residual signal from ALE contains second-order cyclostationary components and stationary white noise. In cyclic Wiener filter, the frequency shift version of the residual signal is used as new input. The frequency shifted versions are $x_\eta(n) = x(n) * e^{j2\pi n\eta}$, where η containing all the cyclic frequencies: $\alpha_0, \alpha_1, \ldots, \alpha_{(L-1)} \in A$. Each output of the filter-bank $h_\eta(n)$ is $y_\eta(n)$. The summation $y(n)$ is considered as the estimation of the expected output $d(n)$. The error function can be expressed as $e(n) = d(n) - y(n)$. In cyclic Wiener filter all the weight coefficients of the filter-bank should be adjusted simultaneously to minimize the mean square error. Figure 4 shows the sketch map of cyclic Wiener filter.

The performance of cyclic Wiener filter might be influenced by many factors, such as the number of cyclic frequencies, the error of estimated cyclic frequencies and the level of noise [20]. Herein, the background noise is considered as invariable, and the error of estimated cyclic frequencies is also considered as constant depending on the accuracy of the estimated method. So we just study the impact of the number of cyclic frequencies used in cyclic Wiener filter.

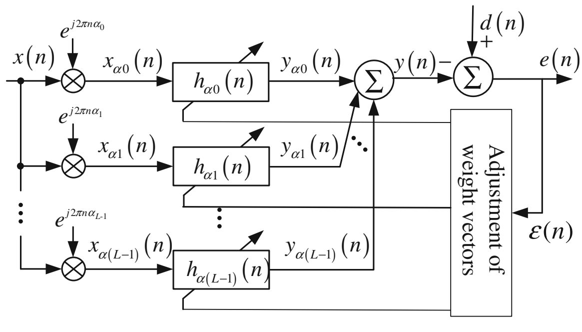

Fig. 4 Sketch map of cyclic Wiener filter

For a bearing signal, its cyclic frequencies and their harmonics are all characteristic frequencies. Theoretically, the number of cyclic frequencies used in cyclic Wiener filter should be chosen much more so as to reduce the noise energy, which means to enhance the performance of the method. While in practical, one is also faced with two trade-offs. Firstly, the adaptive algorithm used for cyclic Wiener filter is comparatively complex. If too many cyclic frequencies were used, the quantity of computation will become quite enormous, which will reduce the accuracy of the algorithm. Secondly, rolling bearings present pseudo-cyclostationarity because of the random slip of rolling elements. The calculated fundamental frequencies are only pseudo-cyclic frequency, so the higher harmonics will smear more and more. So the number of cyclic frequencies used in the algorithm should not be too large.

4 Simulation Analysis

The proposed method is demonstrated on a simulated gearbox signal. The gearbox signal with an inner race failed bearing is simulated. The inner race fault frequency f_i 102 Hz. The sampling frequency f_s is 12,800 Hz. The shaft rotational frequency f_r is 13 Hz, and the gearmesh frequency f_Z of gears is 533 Hz. The natural frequency of the system f_n is 3,000 Hz. Some white noise is also added to produce a realistic signal-to-noise ratio (SNR) of −10 dB. Figure 5 gives the simulated gearbox vibration signal. The time waveform and the amplitude spectrum are respectively given in Fig. 5a, b. In Fig. 5b it can be seen that the main energy is corresponded

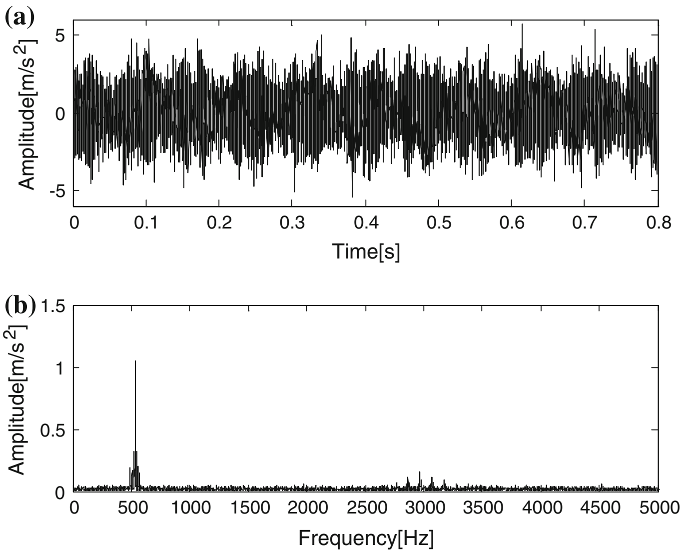

Fig. 5 Simulated gearbox signal. **a** Time waveform. **b** FFT

with the gearmesh frequency f_Z. It is difficult to know whether the key parts of the gearbox are healthy or not. We should remove the periodic components first.

Figure 6a displays the time waveform of the first-order cyclostationary components obtained from ALE, and Fig. 6b gives the time waveform of the residual signal. Figure 7 illustrates the power spectral density of the original signal, the first-order cyclostationary signal and the residual signal. In Fig. 7 it can be seen that the energy of the residual signal which is close to the original signal is much higher than that of the first-order cyclostationary signal. We suppose that the gear was healthy and maybe some faults occurred on the bearing. In Fig. 6b it can be seen that the second-order cyclostationary signal is corrupted by the additive background noise. We should perform cyclic Wiener filter to the residual signal to clearly analyse the second-order cyclostationary signal.

Figure 8a displays the time waveform of second-order cyclostationary signal obtained from cyclic Wiener filter. In Fig. 8a, it can be seen that there are many obvious periodic impulses, indicating the existence of second-order cyclostationary components. Envelope spectrum analysis is a well-known method to extract bearing defect frequency in industrial field [21]. The envelope spectrum of the second-order cyclostationary signal is given in Fig. 8b. It can be seen that the characteristic frequencies are f_i and its harmonics modulated by f_r, which implies the occurrence of the inner race fault.

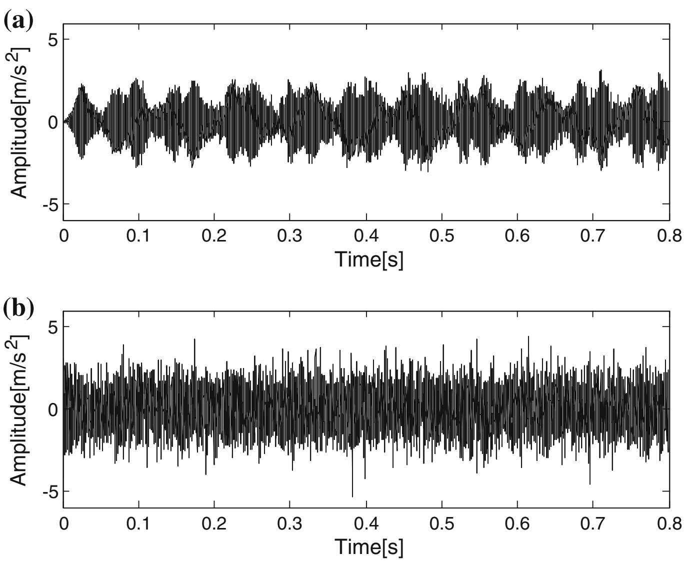

Fig. 6 The time waveform obtained from ALE. **a** Time waveform of first-order cyclostationary components. **b** Time waveform of the residual signal

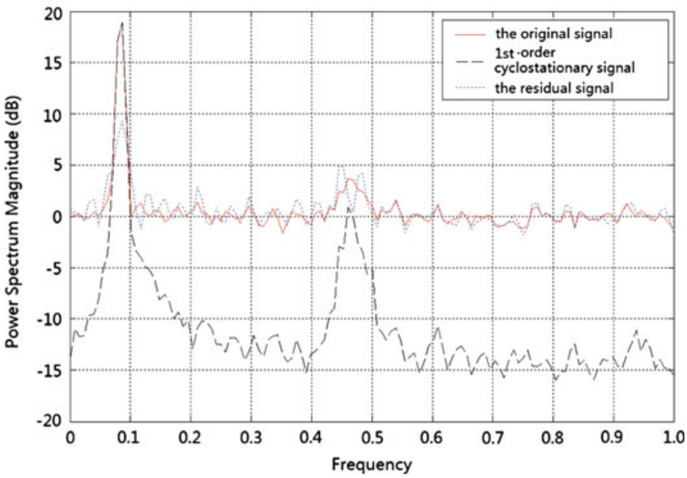

Fig. 7 Power spectral density comparison of the simulated signal

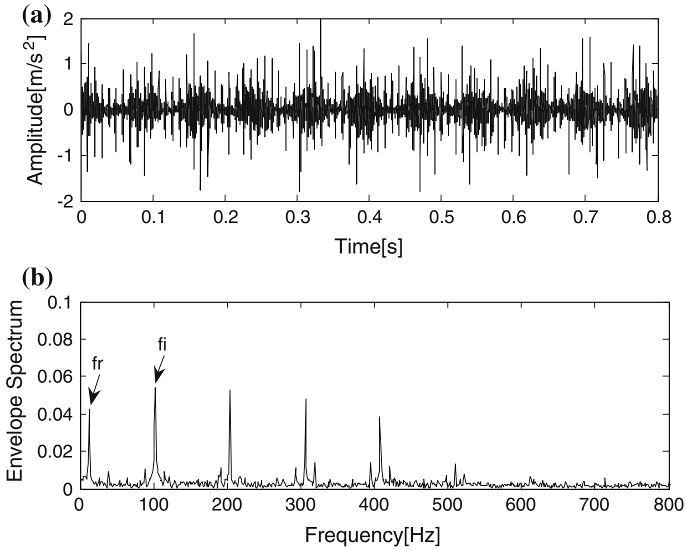

Fig. 8 Second-order cyclostationary signal obtained from cyclic Wiener filter. **a** Time waveform of second-order cyclostationary signal. **b** Envelope spectrum of second-order cyclostationary signal

5 Experiment Validation

Machinery Fault Simulator (MFS) is used to collect vibration data. Herein, the experiment rig and the experimental data are provided by Centre of Prognostic and System Health Management of City University of Hong Kong. One rolling ball bearing (model: MB ER-12K) with outer race fault and one gearbox (model: Hub City M2) with all good components are installed to MFS. Two bearings are supporting the shaft, which is rotated by a HP variable frequency AC motor. Two belts are used to connect the shaft and the gearbox. Four single axis accelerometers (model: industrial ICP accelerometer 608A11) are mounted on two outboard bearing houses in vertical direction (s1, s4) and horizontal direction (s2, s3). One tri-axial accelerometer (model: industrial ICP accelerometer 604B31) is mounted on the top of the gearbox to acquire three path signals in x, y, z axis direction (s5, s6, s7). The test rig is shown in Fig. 9.

One group of 6 s points is collected with the sampling frequency 75 kHz. The shaft rotational frequency is 24 Hz. The data collected by sensor 5 is studied, which nears to bearing 1 with an outer race fault, but influenced by the gearmesh effect of one good gearbox.

The time waveform and the amplitude spectrum of the data collected in sensor 5 are given in Fig. 10a, b. In Fig. 10, we could not get any useful information. We should first remove the periodic component and reduce the background noise. Firstly, the first-order cyclostationary component can be obtained from ALE. The power spectral density of the original signal, the first-order cyclostationary signal and the residual signal after ALE are calculated and shown in Fig. 11. In Fig. 11 it can be seen that the energy of the residual signal is about 30 dB higher than that of the first-order cyclostationary signal. We should perform cyclic Wiener filter to the residual signal to clearly analyze the second-order cyclostationary signal.

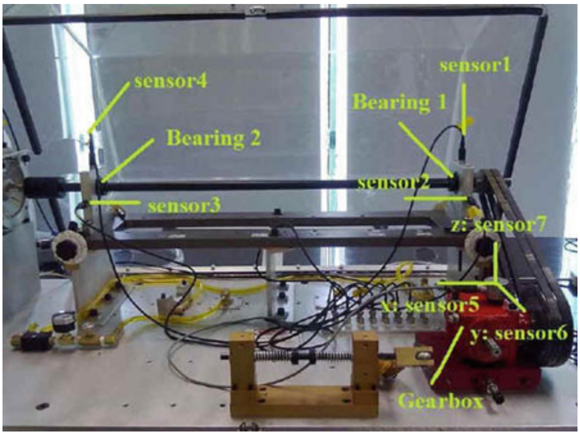

Fig. 9 The experiment test rig

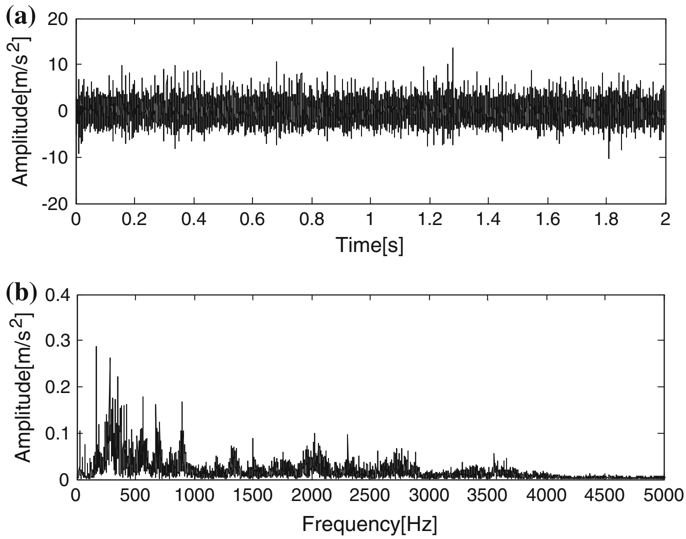

Fig. 10 The time waveform and amplitude spectrum of data in sensor 5. **a** Time waveform. **b** FFT

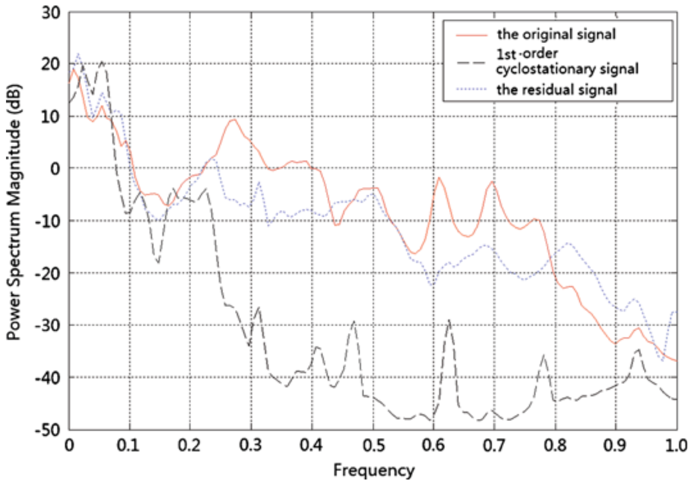

Fig. 11 Power spectral density comparison of the tested signal

The time waveform and envelope spectrum of second-order cyclostationary signal obtained from cyclic Wiener filter are given in Fig. 12a, b. In Fig. 12b it can be seen that the characteristic frequencies are f_o and its harmonics, which implies the occurrence of the outer race fault. The analyzed bearing is confirmed as outer race fault after the test. The analysis results of the experiment data verify the validity and effectiveness of the cyclic adaptive filter in gearbox fault diagnosis.

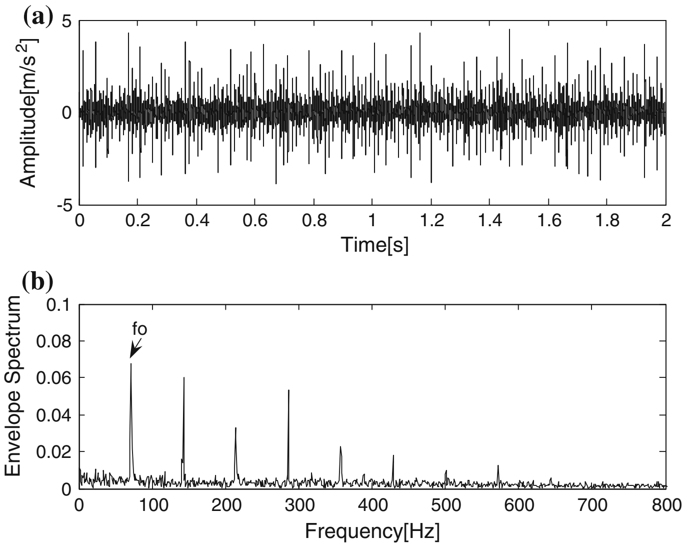

Fig. 12 Second-order cyclostationary signal obtained from cyclic Wiener filter. **a** Time waveform of second-order cyclostationary signal. **b** Envelope spectrum of second-order cyclostationary signal

6 Conclusion

In industry field, the gearbox fault diagnosis under strong background noise has been paid more and more attention. The present paper introduces a method based on cyclic adaptive filter dedicated to this difficult task. The periodical components are first extracted by adaptive line enhancer, and the residual signal is filtered by cyclic Wiener filter. The noise component can be optimally filtered by cyclic Wiener filter. Based on the proposed method, the condition of each parts of gearbox can be well monitored.

Acknowledgments Support for this work from Natural Science Foundation of China (Approved Grants: 51105243 and 51035007) is gratefully acknowledged.

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Bearing Replacement Interval Extension for Helicopters

Reuben Lim, David Mba and Emmanuel O. Ezugwu

Abstract For operators and maintainers, extension of maintenance intervals is desired to alleviate costs. For aircraft and helicopter components, traditional failure time based reliability assessment methods can seldom be applied as the reliability is often very high and defect occurrence tends to be rare. In this paper, methods to develop a conservative estimate of the reduction in reliability are explored. A case study is performed on available data from a helicopter gearbox bearing to evaluate the extension of bearing replacement interval from 2,000 to 3,000 h. The basic reliability assessment using the bearing rated life and Weibull plot equation is first carried out. The basic assessment is then improved by building confidence bounds using the Monte Carlo Simulation method. The assessment then takes into consideration data from flight usage monitoring and lastly, a probabilistic modeling of damage accumulation is attempted. From this investigation, a conservative estimate of the change in reliability from interval extension is obtained.

1 Introduction

When an aircraft or helicopter is first introduced into service, its initial maintenance program tends to be conservative [1]. As more service experience is gained, extension to maintenance intervals is desired to alleviate costs. The potential risk of failure from such an extension has to be quantified to show that it is kept within an acceptable level. A conservative estimate of the drop in reliability during the extended period is a key measure for maintainers and decision makers in accepting such an extension. For aircraft and helicopter components, especially Flight Safety Critical Aircraft Parts (FSCAP), the reliability are often very high and defect

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_16

occurrence tends to be rare. As such, traditional failure time based reliability assessment methods can seldom be applied. In this paper, methods which may be applied by maintainers to develop a conservative estimate of the reduction in reliability are explored. A case study is performed on available data from a helicopter gearbox bearing to evaluate the extension of bearing replacement interval from 2,000 to 3,000 h. The reliability assessment using the bearing L_{10} life and Weibull plot equation is first carried out. The basic assessment is then improved by building confidence bounds using the Monte Carlo Simulation method. The assessment then takes into consideration data from flight usage monitoring and lastly, a probabilistic modeling of damage accumulation is attempted.

2 Helicopter Gearbox Bearing

An angular contact bearing in a helicopter gearbox was assessed for this investigation. The rated L_{10} life; the life at which 10 % of the bearings are expected to fail is shown in Table 1. The rated L_{10} life is generally known but if unavailable, it could be calculated from standards such as DIN or BS 281. However, life adjustment factors such as material and surface information may not be readily available. In such instances, it could be assumed that the replacement interval of the bearing is the L_1 life particularly if there are no failed bearings from past replacement were found. The Weibull slope, $e = 1.11$ for bearings are generally accepted based on work from Lundberg and Palmgren [2].

3 Reliability Assessment Based on Bearing L_{10} Life

As the rated L_{10} life of the bearing is itself a measure of reliability, the change in reliability of the bearing can of course be obtained directly from the general Weibull plot equation [3] given by:

$$lnln\left(\frac{!}{!}\right)^{=eln}\left(\frac{!}{!_{!}}\right), \quad where\ 0<L<\infty,\ 0<R<1 \tag{1}$$

In Eq. (1), $\left(\frac{!}{!}\right)$ is the percentage of bearings surviving at time L and L_β is the *lnln* characteristic life of the bearing. For bearing replacement interval at $L = 2{,}000$ h

Table 1 Bearing specifications

Bearing type	Angular contact bearing
L_{10} life (h)	14,700
L_β characteristic life (h)	111,632
Weibull slope, e	1.11

and e = 1.11, reliability of the bearing, R = 0.9886. If the interval is extended to L = 3,000 h, the reliability of the bearing reduces to R = 0.9821. The additional risk, ⊗***R*** is thus 0.0065. This approach is simple to apply but it assumes a fixed L_{10} life and e = 1.11. If there are variations in these parameters, the reliability assessment will change accordingly.

4 Building Confidence Bounds Using Monte Carlo Simulation Testing

Helicopter gearboxes and its components such as bearings tend to be produced in small numbers and the number of units tested is usually small due to high cost. As such, it is cost prohibitive to determine variation in component L_{10} life from physical test data. Alternatively, a Monte Carlo Simulation method may be applied to determine variation in L_{10} life. Vleck et al. [4] applied such simulation for "virtual bearing testing" to determine variations in bearing life for any number of bearings tested.

4.1 Determination of Bearing Inner and Outer Race Life

Before performing the Monte Carlo simulation, the rated life of the inner race and outer race has to be calculated first. From [3], the bearing fatigue life formula is given by:

$$L =$$

$$L = \left(\frac{C}{F_!}\right)^! \tag{2}$$

and the outer race life, L_{or} to inner race life, L_{ir} can be determined to be:

$$\frac{L_{!"}}{L_{!"}} = \left(\frac{C_{!"}}{C_{!"}}\right)^! \left(\frac{F_{!"}}{F_{!"}}\right)^! \approx \left[\left(\frac{1-\gamma}{1+\gamma}\right)^{!.!"!!\urcorner} \left(\frac{J_!}{J_!}\right)^!\right]^! \tag{3}$$

where, C_{ir} and C_{or} are the dynamic load capacity of the inner and outer race. $F_{,ir}$ and F_{or} are the applied load on the inner and outer race. γ is given by $dcos(\alpha/d_m)$. J_1 and J_2 are the factors relating mean load on a rotating and non-rotating raceway to the maximum raceway normal load under nominal load distribution factor, ε = 0.5. From [4], Zaretsky's rule follows "For radially loaded ball and roller bearings, the life of the rolling element set is equal to or greater than the life of the outer race.

Let the life of the rolling element set (as a system) be equal to that of the outer race". The bearing rated life L_{sys} and its sub-component is then given by:

$$\left(\frac{1}{L_{!''!}}\right)^{!} = \left(\frac{1}{L_{!''}}\right)^{!} + 2\left(\frac{1}{L_{!''}}\right)^{!}, \quad where\ L_{!''} = L_{!''} \qquad (4)$$

It should be noted that Zaretsky's rule differs from the method of Lundberg and Palmgren from [2] as the latter does not include the lives of the rolling elements it is considered much longer compared to the races. From Eq. (3) the life ratio of the outer to inner race is 0.349. Applying this ratio to Eq. (4) together with L_{sys} = L_{10} = 14,700 h, L_{ir} and L_{or} were determined to be 22,719 and 65,131 h.

4.2 Monte Carlo Simulation Testing of Bearing Life

In the Monte Carlo Simulation approach by Vleck et al. [4], sub-components consisting of the inner race, outer race and ball bearings are grouped in separate virtual bins. Within each virtual bin, the sub-components are ordered according to the number of sets tested and assigned the corresponding life based on the Weibull plot. For example, for n = 100 bearings tested, the inner race virtual bin will contain 100 inner races with life L_2, L_4, $L_{100i/n}$, ...L_{100} for i = 1:n. The bearing is randomly assembled without replacement and the life is then based on the sub-component with the lowest life as illustrated in Fig. 1. This is repeated for any number of n bearings. The L_{10} and e of the bearing set can be determined by fitting the bearings' life back into the Weibull distribution as shown in Fig. 2.

This procedure is then repeated for multiple sets of bearings to obtain the variations in L_{10} and e. For the Monte Carlo testing, the number of bearings to be tested will affect the amount of variation in the rated life. The number is

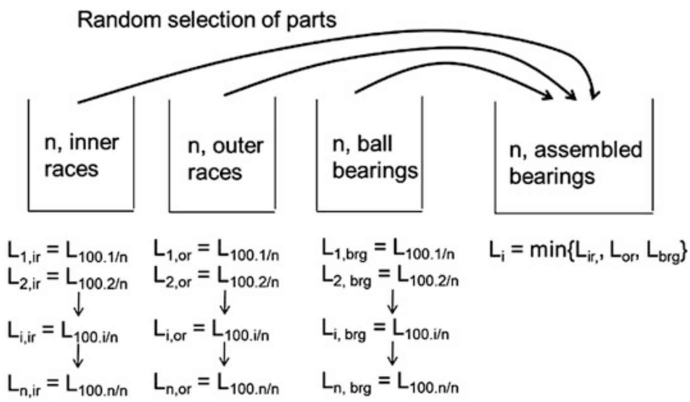


Fig. 1 Virtual assembly of bearings parts

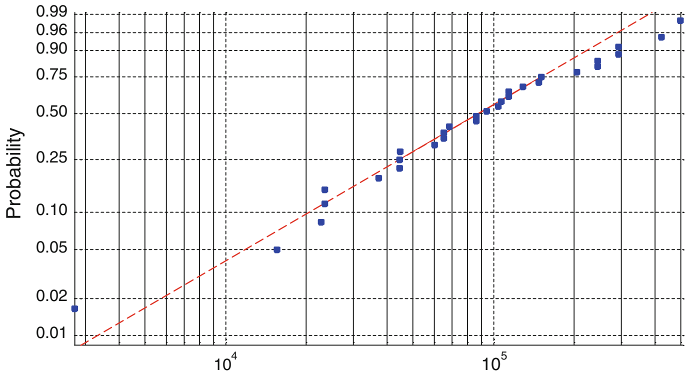


Fig. 2 Weibull plot for a set of virtual bearing

recommended to be reflective of the number of bearings in the fleet or have previously undergone replacement so that the failure hours of any bearing defects experienced prior to replacement can used to measure the lower bound variation. In this case, the number of bearing in the virtual testing is n = 30. The Monte Carlo Simulation is performed using script written in MATLAB and the virtual testing of the 30 bearings was repeated 1,000 times to estimate the variation in the Weibull Slope, *e*. The Weibull plots and the distribution of *e* from the virtual test is shown in Fig. 3. The 90 % confidence bound for *e* is [0.92, 1.46] and for L_{10} is [7520, 26700] (Fig. 4).

By applying the Monte Carlo simulation, the variability in L_{10} and *e* are considered and a confidence was constructed to assess the change in reliability from the interval extension. Although a more conservative estimate is available through the confidence bounds, this assessment is based on bearing design parameters only and does not consider in-service experience on the bearing usage (Table 2).

5 Reliability Applying Usage Monitoring Data

In a usage monitoring application, the actual usage of components are monitored and service life can be updated instead of being dependent on "worst case" usage scenarios adopted during design. Building upon the foregoing analysis in Sect. 4, usage monitoring data is used to evaluate the usage severity of the bearing. In this case, the usage is derived from the torque spectrum of the gearbox and both the design and actual usage spectrum of the bearing are known. The spectrum plot is shown in Fig. 5 and it can be seen that the percentage time spent at higher torque levels is lower in the actual usage compared to the design usage. As such, the life of the bearing can be expected to be longer as the actual usage is less severe. The bearing load is proportional to the applied torque load and expressed as % Torque.

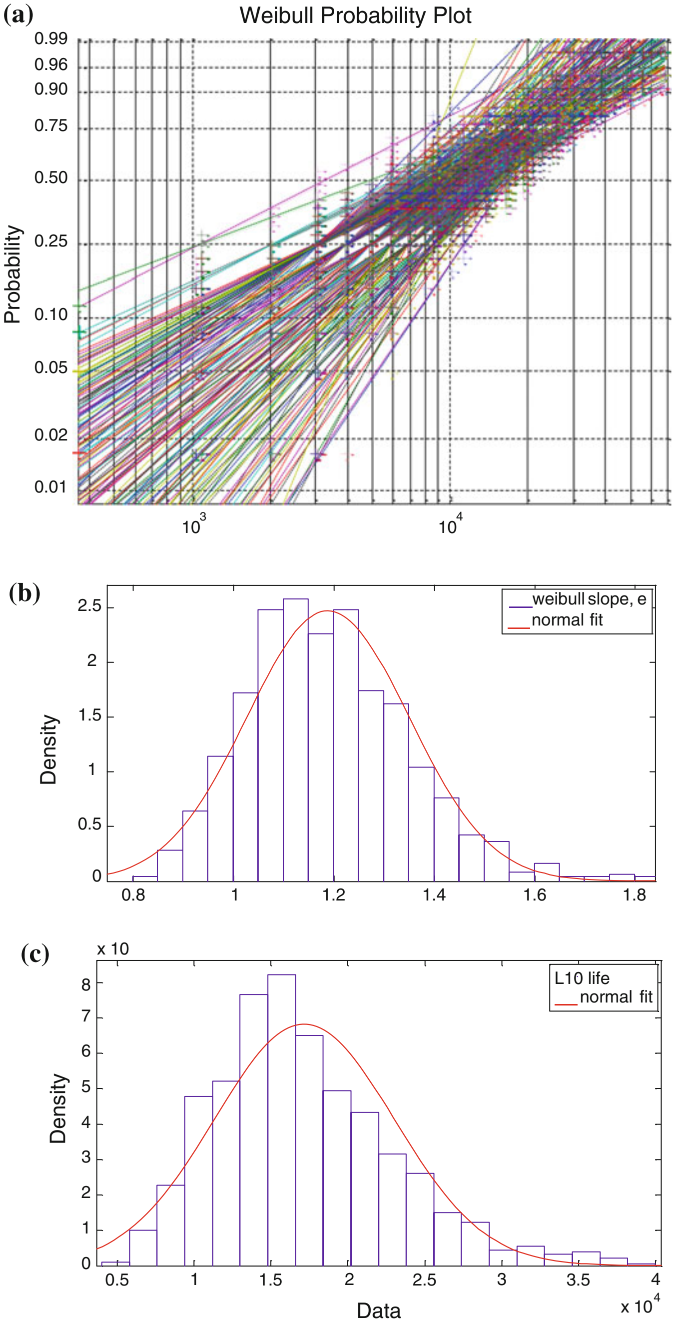


Fig. 3 Monte Carlo Simulation of bearing test (**a**) and resulting distribution of e (**b**) and L_{10} (**c**)

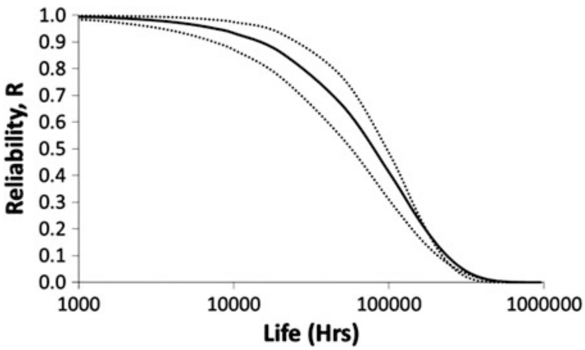


Fig. 4 Reliability plot versus time with 90 % confidence bounds in Weibull slope, *e*

Table 2 Reliability of bearing at different replacement interval with 90 % confidence bound

Weibull slope, *e*	1.11	1.46	0.92
L_{10} life	14,700	26,700	7,520
R at 2,000 h	0.9886	0.9976	0.9692
R at 3,000 h	0.9821	0.9957	0.9557
⊗**R**	0.0065	0.0019	0.0135

From [3], the mean effective load is developed from the variable loading in the usage spectrum and is given by:

$$F_{!} = \left(\sum \frac{F_{!}^{!} l_{!}}{L_{!'',!}}\right)^{!} = \left(\sum_{F_{!}^{!} t^{!}}\right)^{!}_{!}, \tag{5}$$

where t_i is the % usage at F_i, $p = 3$ for angular contact bearing. The mean effective design and actual usage load from Fig. 5 is $F_{m,design}$ = 73.86 % Torque and $F_{m,actual}$ = 70.44 % Torque respectively and the actual usage is less severe by 3.42 % Torque.

From bearing life equation,

$$L_{!''} = \left(\frac{C}{F_{!}}\right)^{!} \tag{6}$$

Based on L_{10} = 14,700 h and $F_{m,design}$ = 73.86 % Torque, the dynamic load capacity, C = 1809.2 % Torque. Note that the dynamic load capacity of the bearing C is derived from the effective mean load of the design spectrum and the L_{10} life. With a reduced effective mean load, $F_{m,actual}$ = 70.44 % Torque, the updated L_{10} = 16,947 h. With the updated L_{10} life, the reliability assessment methods in

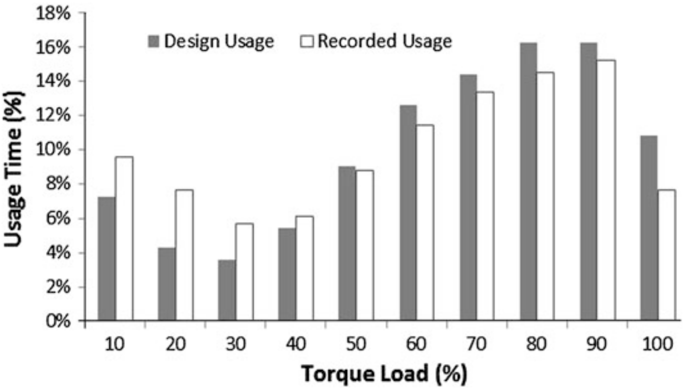


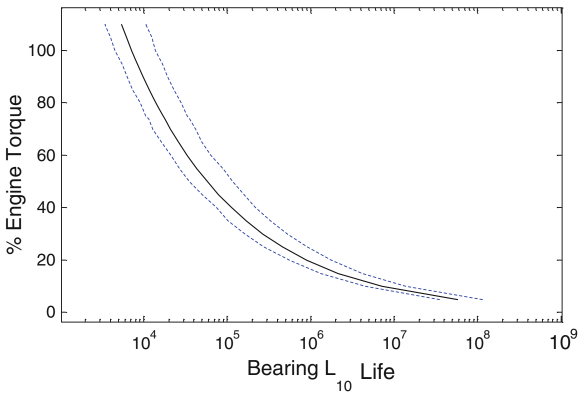
Fig. 5 Percent usage time against load for design and actual load spectrum

Table 3 Reliability of bearing at different replacement interval with 90 % confidence bound

Weibull Slope, *e*	1.11	1.46	0.92
L_{10} life	16,947	31,200	8,600
R at 2,000 h	0.9902	0.9981	0.9732
R at 3,000 h	0.9847	0.9966	0.9612
⊗**R**	0.0055	0.0015	0.0120

Sects. 3 and 4 are applied with results shown in Table 3. This procedure could be performed for different effective mean load and Fig. 6 shows the variation in L_{10} against % Torque with 90 % confidence bounds.

Fig. 6 Variation in L_{10} against % Torque with 90 % confidence bounds



6 Probabilistic Modelling of Damage Accumulation

In practice, the L_{10} is often treated as the fatigue life from which servicing and replacement schedule are based. If the L_{10} is taken as the fatigue life of the bearing, damage accumulation models may also be applied to assess the bearing reliability. From another perspective, 10 % of the bearing with fatigue life L_{10} can be evaluated using damage accumulation models. This will be a conservative approach as the L_{10} is the fatigue life that 10 % of the bearing is expected to fail. When determining the effective mean load in the preceding section, the Palmgren-Miner Rule is assumed. From [3], the bearing fails when the damage D, accumulates to the damage threshold, D_{cr} = 1, where

$$D_{!''} = \sum_{!!!}^{!!!} \frac{l_!}{L_!} = 1 \tag{7}$$

$$D = \sum^{!!!} \frac{l_!}{L_{!'',!}} = \sum_{!!!}^{!!!} \frac{F_!^!}{C} l_! \quad \textit{for n load levels} \tag{8}$$

The damage accumulation from direct use of Miner's Rule however, is a deterministic approach which does not account for the stochasticity in the process. In Fig. 7, the damage accumulation is modeled with a probabilistic approach where both the D_{cr} and D are treated as random variables with a probability density function (pdf). In this way, stress strength interference models can be applied and the reliability of the bearing can be viewed from a probabilistic view from its damage accumulation.

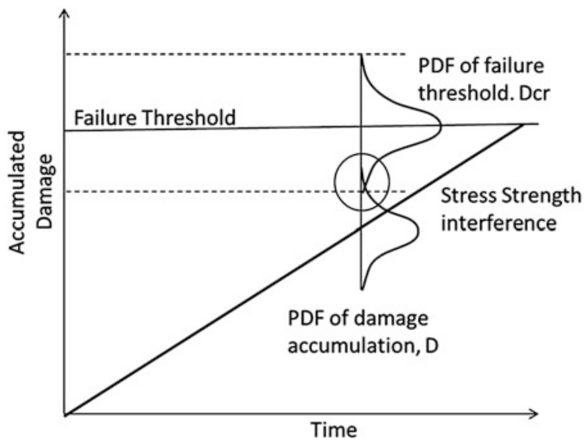


Fig. 7 Probabilistic modelling of damage accumulation

6.1 Probabilistic Damage Accumulation Model

Rathod et al. [5] proposed a methodology for such probabilistic modelling of fatigue damage accumulation. The method employs the linear damage accumulation model of Palmgren-Miner, a probabilistic S-N curve of the subject component and assumes a one to one transformation between the damage accumulation pdf and the fatigue life pdf. The following assumptions have been made in applying the model:

(1) Fatigue failure occurs when damage accumulation (D) reaches the threshold damage (D_{cr}), where $E(D_{cr}) = 1$.
(2) The threshold damage or critical damage has the same distribution as the damage accumulation measure.
(3) When usage life is equal to the fatigue failure life, the variability of threshold damage accumulation (σ^2_{Dcr}) is equal to the variability of damage accumulation measure (σ^2_D). The variability of damage accumulation measure continuously increases with usage life but when usage cycle reaches to fatigue failure level, the corresponding variability is assumed.

From Fig. 6, it can be seen that the relationship between bearing life and applied load is similar to the S-N curve used in fatigue analysis. The S-N curve equation is given by,

$$N_{!}S^{!} = A \tag{9}$$

where, N_f is the cycle to failure at stress level, S. m is the slope parameter and A is the fatigue strength constant. The bearing life equation for different load levels can be expressed in similar form as:

$$L^{!'',!}F^{!_!} = C^{!} = A \tag{10}$$

As such, the probabilistic damage accumulation model can be easily adapted for bearing application. For the general case under variable loading, the variation or standard deviation of in damage with usage life is given by:

$$\sigma_{!} = \sqrt{\sum_{!!!}^{!}\left(\frac{F_{!}^{!}}{C_{!}}l_{!}\left(\frac{\sigma_{!_{!'',!}}}{L_{!'',!}}\right)\right)^{!}},\ \textit{for n load levels} \tag{11}$$

and the critical damage threshold is given by:

$$\sigma_{!!} = \sqrt{\sum_{!!!}^{!}\left(\frac{!^{!}}{!_{!}}L_{!'',!}\left(\frac{!_{!_{!'',!}}}{!_{!'',!}}\right)\right)^{!}},\ \textit{for n load levels} \tag{12}$$

The reliability of the bearing applying stress strength interference method is then given by:

$$
\begin{aligned}
R &= 1 - \varnothing\left(-\frac{(\mu_{!_!} - \mu_!)}{\sqrt{\sigma^!_{!_!} + \sigma^!_!}}\right) \\
&= 1 - \varnothing\left(-\frac{\left(1 - \sum^!_{!!!} \frac{!^{!'}}{!_!} l_i\right)}{\sigma^!_{!_!} + \sum^!_{!!!}\left(\left(F^!_!/C^!\right) l_! \ \left(\sigma_{!_{!'',!}}/L_{!_{!'',!}}\right)\right)^!}\right)
\end{aligned}
\tag{13}
$$

6.2 Reliability Assessment of Bearing Using Probabilistic Damage Accumulation Model

For the probabilistic damage accumulation model to be applied, a probabilistic S-N curve for the bearing is required. However, this has already been obtained in Sect. 5, where the variation in bearing L_{10} against % Torque was derived. At each % Torque load level, a normal distribution is fitted to the results from the Monte Carlo Simulation to obtain the standard deviation of the $\sigma!_{!''}$. The $\sigma!_{!''}$ is observed to increase with decreasing load with a coefficient of variation, c_v of $\sim$0.36 across the load levels. This agrees well with [5] which mentioned that variability in fatigue life is lower at higher stress levels. This is also shown from experiments by Rosado et al. [6] where it was observed that the variance in spall growth increases with reduction in applied loading. Their experiments on M50 bearings also showed a c_v of $\sim$0.21 and $\sim$0.36. For a single equivalent load at $F_{m,actual}$ = 70.44 % Torque, C = 1809.2 % Torque, the mean bearing life bearing life L_{10} = 16,947 h. With $cv \approx 0.36$, $\sigma!_{!''}$ = (0.36)(16,947) = 6,101 h. As such, the bearing life is distribution at 70.44 % Torque is given by N(16947, 6101). The critical damage threshold can be obtained from Eq. (10) to be σ_{Dc} = 0.36. In this case, σ_{Dc} is equal to cv as there is only one load level. With these parameters, the reliability of the bearing against usage time can be obtained. The result is shown in Fig. 6 together with results performed for the upper and lower bound L_{10} life from Table 3. The reliability assessment for extension of replacement interval from 2,000 to 3,000 h using this approach is summarized in Table 4.

Table 4 Reliability of bearing using probabilistic damage accumulation model

L_{10} life	16,947	31,200	8,600
R at 2,000 h	0.9925	0.9953	0.9811
R at 3,000 h	0.9878	0.9938	0.9562
⊗**R**	0.0047	0.0015	0.0249

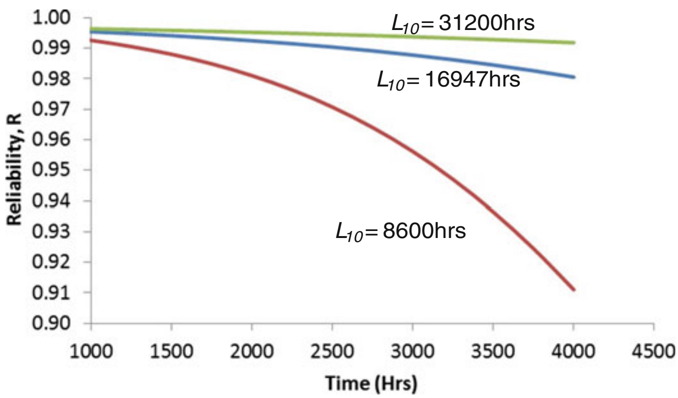


Fig. 8 Reliability of bearing using probabilistic damage accumulation model

The change in reliability, ⊗**R** in Table 4 is lower than that of Table 3 for L_{10} = 31,200 h, marginally lower for L_{10} = 16,947 h and higher for L_{10} = 8,600 h. This is because the variability in accumulated damage increases with usage life. When the usage life being evaluated is small compared to the L_{10} life, (i.e. at 2,000/31,200 h), the variability in accumulated damage is small, thus the ⊗**R** is small. Conversely, when the usage life increases compared to the L_{10} life, (i.e. at 2,000/8,600 h), the variability in accumulated damage increases and the ⊗**R** is larger. As such, the probabilistic damage accumulation model can be less conservative compared to the use of the Weibull plot equation in Sects. 4 and 5 when the usage hours is small compared to the L_{10} life. As the usage hours being evaluated increases, the probabilistic damage accumulation model will provide a more conservative estimate (Fig. 8).

7 Reliability Assessment of Bearing Replacement Interval

The case study begun with a reliability assessment of extending the bearing replacement interval from 2,000 to 3,000 h based on the L_{10} life information and the Weibull plot equation with ⊗**R** = 0.0065. A more conservative estimate accounting for variation in the Weibull slope, e and L_{10} life is then obtained using Monte Carlo Simulation Testing with a higher ⊗**R** = 0.0136. The usage severity of the bearing is then considered by using usage monitoring data from which the updated L_{10} life is obtained. As the actual usage severity is lower than the design usage, the change in reliability from the extension has reduced from previous estimates with ⊗**R** = 0.0120. Lastly, a different approach using probabilistic modeling of the damage accumulation is applied and ⊗**R** = 0.0249 is obtained. In this case study, this approach has the highest ⊗**R** as it accounts for addition variation in the damage accumulation process. In this manner, a conservative estimate of the change in reliability from the interval extension has been developed by considering variation in the bearing, the usage severity and the damage accumulation process.

8 Conclusion

From the case study, a conservative estimate of the change in reliability from interval extension can be obtained with limited available information. Realistic figures for bearing geometry, replacement times and load spectrum have been used in the case study so that the reliability assessment is reflective of in-service application. It is recognized that this work is not substantiated by experimental or field data. However, the goal is to develop a conservative estimate for the purpose of maintenance interval extension. This work could be applied in maintenance escalation work where the amount of extension however is largely based on expert opinions and quantitative substantiated is required.

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Non-intrusive Diagnostic of Middle Bearing of Aircraft Engine

Romuald Rzadkowski, Edward Rokicki, Ryszard Szczepanik and Józef Żurek

Abstract Failure of the middle bearing in an aircraft rotor engine was reported. Tip-timing and tip-clearance analyses were carried out on a compressor rotor blade in the seventh stage above the middle bearing. The experimental analyses concerned both an aircraft engine with a middle bearing in good working order and an engine with a damaged middle bearing. A numerical analysis of the free vibration of the seventh stage blade was conducted to explain the experimental ones. Proposed in this paper is a method to prevent middle bearing failure.

1 Introduction

Rolling element bearings are one of the most essential parts in rotating machinery. During operation, bearings are often subjected to high loading and difficult working conditions, which in turn often lead to the development of defects on the bearing components [1]. One way to increase operational reliability is to monitor incipient faults in these bearings [2–4]. Analytical models for predicting the vibration frequencies of rolling bearings and the amplitudes of significant frequencies with localized defects in bearings have been proposed in [5–8].

FFT is one of the widely used fault detection techniques [9, 10]. The only drawback of FFT based methods is that it is not suitable for non-stationary signals. In recent years, a new time frequency analysis technique, called Wavelet Analysis, was developed. The advantage of Wavelet Analysis is that the non-stationary characteristic of a signal can be easily highlighted in its spectrum [9–13].

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_17

The tip-timing technique is generally used for diagnosing rotor blade displacements during rotation with a wide range of speeds [14, 15]. In this paper the tip-timing technique is used for diagnosing displacements of the seventh compressor rotor blades and the middle bearing close to this stage. Such an analysis is important, because the failure of the middle bearing of an aircraft engine was reported in 1993 [14, 15] (Figs. 1 and 2). In paper [16] the tip-timing and RMS technique was used. In this paper the tip-timing and tip-clearance techniques are used to diagnose middle bearing failure on the basis of compressor 7th stage rotor blade displacements.

Measurements of seventh stage compressor rotor blade vibrations were made using the tip-timing method at the Air Force Institute of Technology in Warsaw. In order to better understand the experimental results, numerical calculations were also conducted for the seventh stage compressor rotor blades using the FE method.

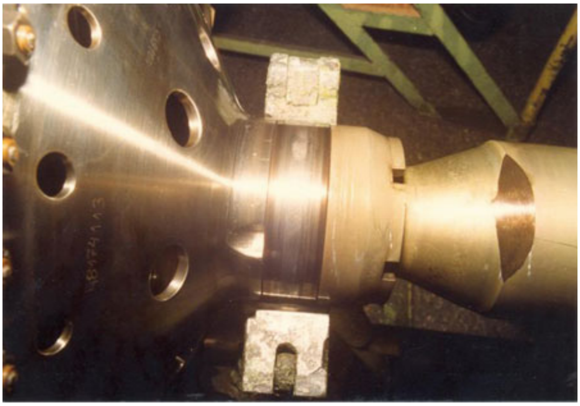

Fig. 1 The inner running track of the aircraft engine middle bearing

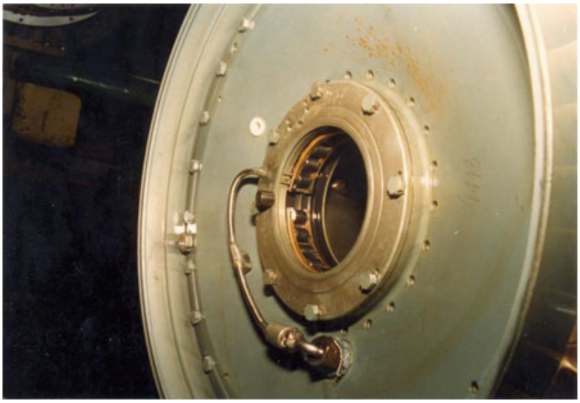

Fig. 2 Damaged elements of the aircraft engine middle bearing

Table 1 Measured and numerically calculated natural frequencies of a seventh stage rotor blade

Mode number	Calculated 0 rpm (Hz)	Experiment 0 rpm (Hz)	Calculated 15,000 rpm (Hz)
1	1765.2	$\langle 1620, 1932 \rangle$	1921.6
2	4913.2	$\langle 4592, 5104 \rangle$	4962.4
3	8247.0	$\langle 7920, 8272 \rangle$	8376.1
4	12621	$\langle 12064, 1256 \rangle$	12,697
5	13867	–	13,903
6	15360	–	15,383
7	20973	–	21,084
8	23368	–	23,440
9	25174	–	25,289
10	30445	–	30,457

2 Numerical Results

The seventh stage rotor blade of an SO-3 engine (close to the middle bearing) was modelled using an FE model and its natural frequencies were calculated (Table 1). The number of natural frequencies is presented in the first column. The second and fourth columns show the calculated natural frequencies for a non-rotating blade and one rotating at 15,000 rpm respectively. The third column presents the natural frequencies obtained experimentally. In real compressors every rotor blade is different, so the natural frequencies of each rotor blade also differ. For example, in our experiment the natural frequencies of seventh-stage rotor blades in the first mode ranged from 1,620 to 1,932 Hz. A comparison between the numerical and experimental results (made for stationary blades) was satisfactory. For example, the first calculated frequency was 1765.2 Hz, whereas in the experiment it was $\langle 1620, 1930 \rangle$ Hz. Measurements were made only up to the fourth blade mode. Figure 3 presents a Campbell diagram for the rotor blade [17], which shows that 7EO, 8EO and 9EO can cause higher rotor blade responses.

3 Numerical Analysis

The tip-timing measurement of the seventh stage compressor rotor blade is presented in Fig. 3. This stage consisted of 48 rotor blades. This graph shows displacements of each of the 48 rotor blades at rotation speeds ranging from 7,000 to 15,500 rpm. As can be seen, 7EO and 8EO create greater rotor blade responses. Each blade responded at a different time (see circled regions in Fig. 4). Tip-timing is a non-contact measurement technique which uses probes mounted in the casing to determine the vibration of all the blades.

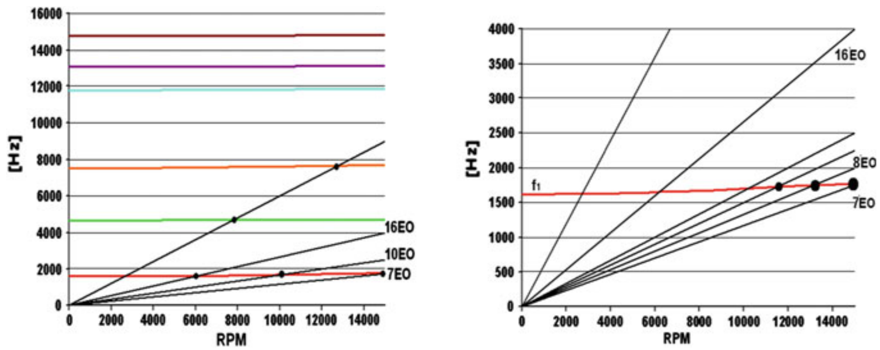

Fig. 3 Campbell diagram of the seventh stage compressor rotor blade of an aircraft engine

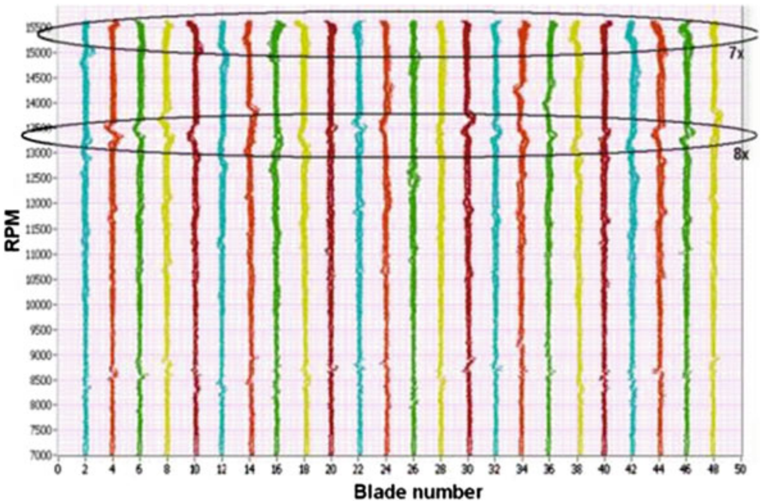

Fig. 4 The tip-timing measurement of the seventh stage compressor rotor blades of an aircraft engine [18]

The results for individual blades could not explain the bearing failure. The entire test run time was divided into short periods of duration T. A variance of all the seventh stage blades was calculated for each T period:

$$Var(t) = \int \left(\frac{1}{N} \sum_{i=1}^{n} x_i^2 - \frac{1}{N} \sum_{i=1}^{n} x_i \right) dt \tag{1}$$

where $x_i(t)$ is the measured signal in period T.

Figure 5 presents the variance dis4placements value of seventh stage rotor blades (Eq. 1) for an assumed test run (plane x-y, rpm vs. time) with the middle bearing working properly. The rotor blade amplitude for 7EO was close to nominal speed (see Campbell diagram Fig. 3). The resonances appeared in the region of 15,000 rpm and were excited by 7EO (see Campbell diagram). There were some other resonances whose origin was difficult to explain using a Campbell diagram of a seventh stage compressor rotor blade, especially at 7,000 rpm.

Figure 5b presents variance versus time results derived from Fig. 5a. The maximal values of the variance amplitude of rotor blades was equal to 1.4 (see Fig. 5b). Experiments were carried out at the Air Force Institute of Technology in Warsaw to reconstruct a real engine failure that was caused by a damaged middle bearing. In order to model the middle bearing failure, metal filings were successively added to the bearing's oil filter while the engine was working. Tip-timing and tip-clearance were used to measure only the 7th stage blade vibration amplitudes because this stage was closest to the middle bearing.

Figure 6a presents the variance displacements values of seventh stage rotor blades (Eq. 1) for an assumed test run (plane x-y, rpm vs. time) with a small amount of metal filings added to the oil filter of the working middle bearing. The rotor blade amplitude for 7EO was close to that of nominal speed (Fig. 3). The highest resonances, variance 61, appeared after the engine had been working for a longer period at 14,000–15,000 rpm (Fig. 6b).

Tip clearance was measured above the seventh stage rotor blades. Eccentricity of rotor motion is one of the symptoms of a problem with the bearing, hence the minimum-to-maximum tip clearance value of tip clearance was shown in Fig. 6c. This clearly shows that the variation value is very small, in the region of 0.95–0.97.

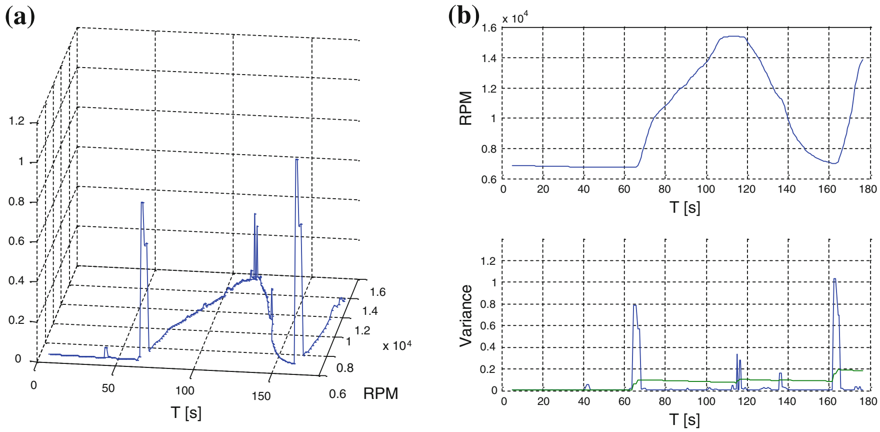

Fig. 5 The variance of vibration amplitudes in seventh stage compressor rotor blades with the middle bearing working properly

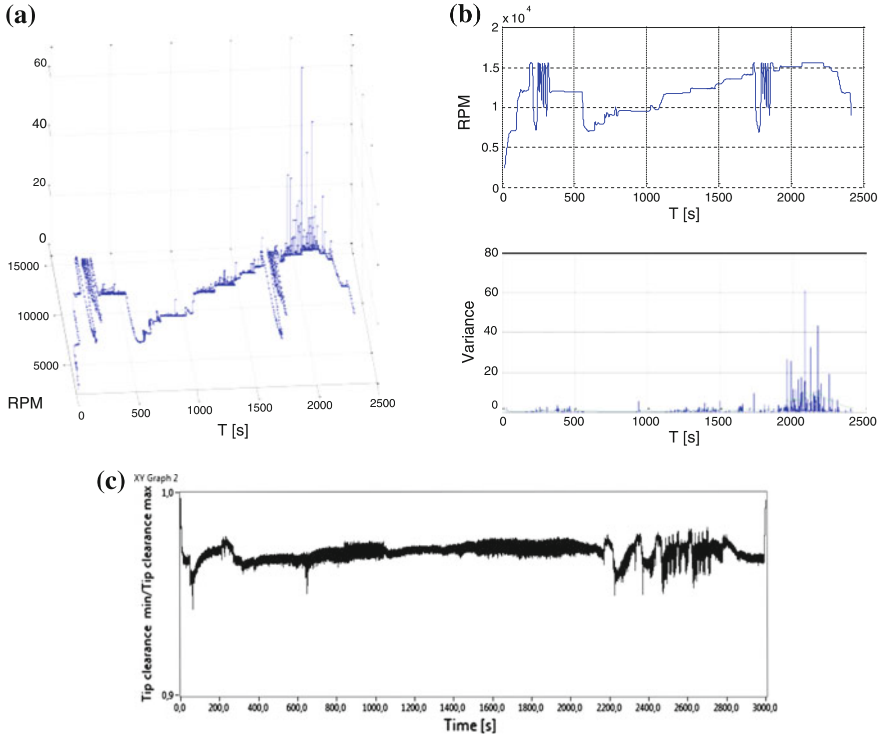

Fig. 6 **a**, **b** The variance of vibration amplitude in seventh stage compressor rotor blade with slightly damaged middle bearing. **c** The measured tip clearance of the seventh stage compressor rotor blade with slightly damaged middle bearing

Figure 7a presents the variance displacements value of seventh stage rotor blades (Eq. 1) for an assumed test run (the plane x-y, RPM vs. time) with more metal filings added to the working bearing oil filter. The maximal rotor blade amplitude for 7EO was close to the nominal speed (see Campbell diagram Fig. 3). The maximal variance value of rotor blade amplitudes decreased from 61 (Fig. 6) to 46 (Fig. 7).

In the next test, with yet more metal filings added to the bearing oil filter, the 7th stage rotor blades began to rub against the casing occasionally after 2,000 s (Fig. 8).

Figure 8a presents the variance displacements value of seventh stage rotor blades (Eq. 1) for an assumed test run (plane x-y, RPM vs. time) with the working middle bearing on the brink of failure. The maximal rotor blade amplitude for 7EO was close to the nominal speed (see Campbell diagram Fig. 3). In Fig. 8b we see more peaks with amplitudes gradually decreasing to 46 (from 45 in Fig. 7b), at which point the bearing failed and the 7th stage blades started rubbing against the casing.

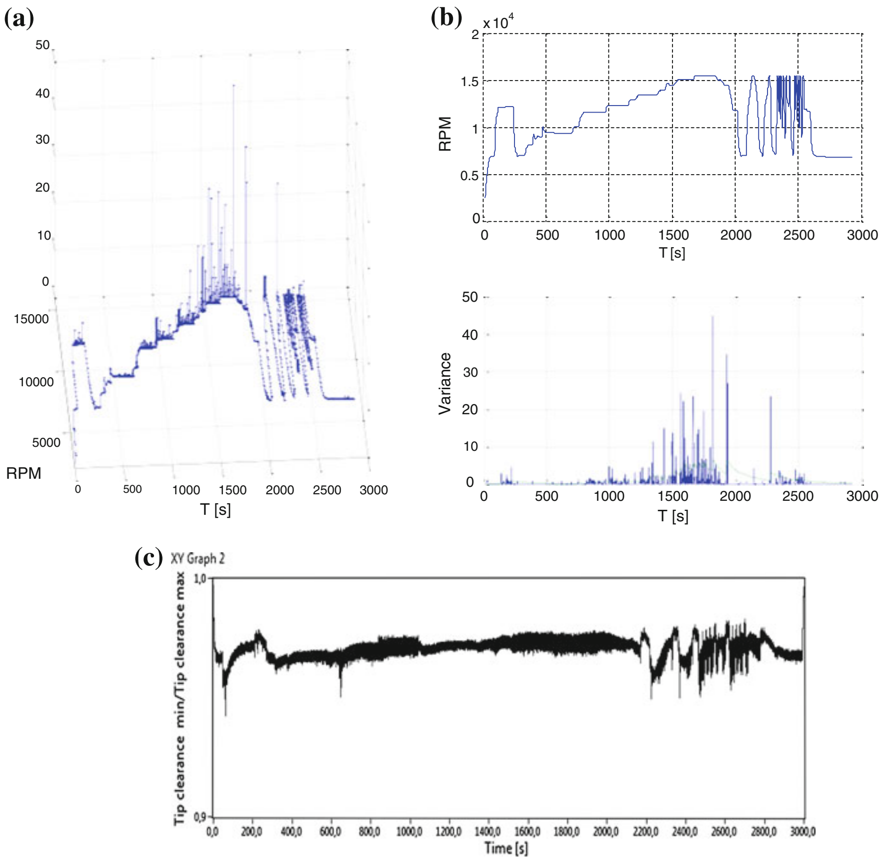

Fig. 7 **a**, **b** The variance of vibration amplitude in seventh stage compressor rotor blade with slightly more damaged middle bearing. **c** The measured tip clearance of the seventh stage compressor rotor blade with slightly more damaged middle bearing

Maximum-to-minimum tip clearance increased from 0.93 to 1.97. Here the sampling for tip-clearance was 500 kHz, therefore not sufficient to reveal the rubbing appeared towards the end of test. The sampling for tip-timing was 80 MHz, and therefore better able to show the rubbing process through greater variance.

In the final test (Fig. 9), 7th stage rotor blade rubbing was so severe that, after 300 s, the engine had to be stopped and the bearing was found to be in a plastic state.

Figure 9a presents the variance value of the seventh stage rotor blades (Eq. 1) for an assumed test run (plane x-y, RPM vs. time) with a fully damaged middle bearing. In Fig. 9b we see more peaks with amplitude variance increasing to 10.3, at which point the bearing failed and the 7th stage blades started rubbing against the

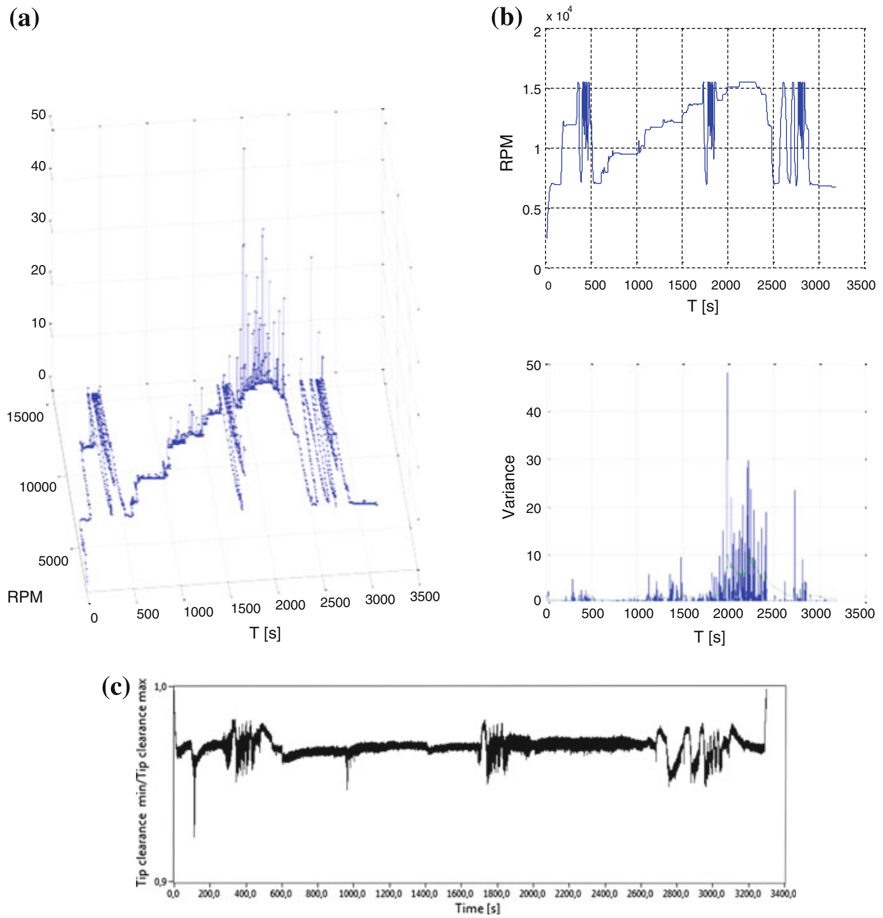

Fig. 8 **a**, **b** The variance of vibration amplitude in seventh stage compressor rotor blade with significantly damaged middle bearing. **c** The measured tip clearance of the seventh stage compressor rotor blade with significantly damaged middle bearing

casing. In comparison with a normally working engine, the variance values increased from 1.04 (see Fig. 5b) to 10.3 (see Fig. 9b). However, this increase only occurred in the region of 190–200 s. Next, when the state of the bearing became plastic, it rapidly decreased, remaining reduced to the end of the test. The tip-clearance minimum-to-maximum value was low, 0.91–0.96, for a longer period of time see time, up to 294 s (Fig. 9d). In that time zero clearance was not visible on account of low sampling (500 kHz). In the 294–310 range (Fig. 9f) the tip-clearance value approached zero. The trajectory of the rotor blades with near zero tip clearance is shown in Fig. 10.

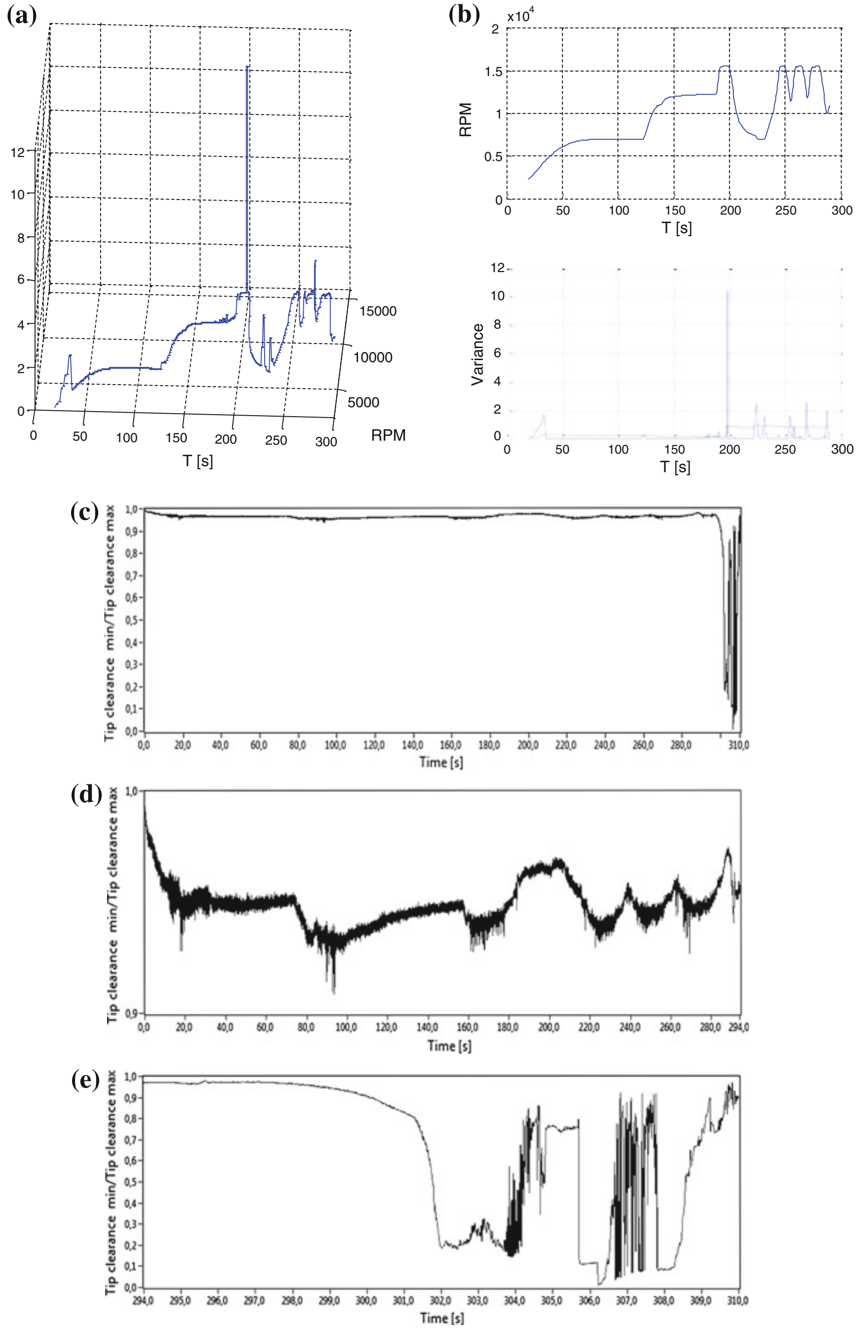

Fig. 9 **a**, **b** The variance of vibration amplitude in seventh stage compressor rotor blade with fully damaged middle bearing. **c–e** The measured tip-clearance of the seventh stage compressor rotor blade with fully damaged middle bearing

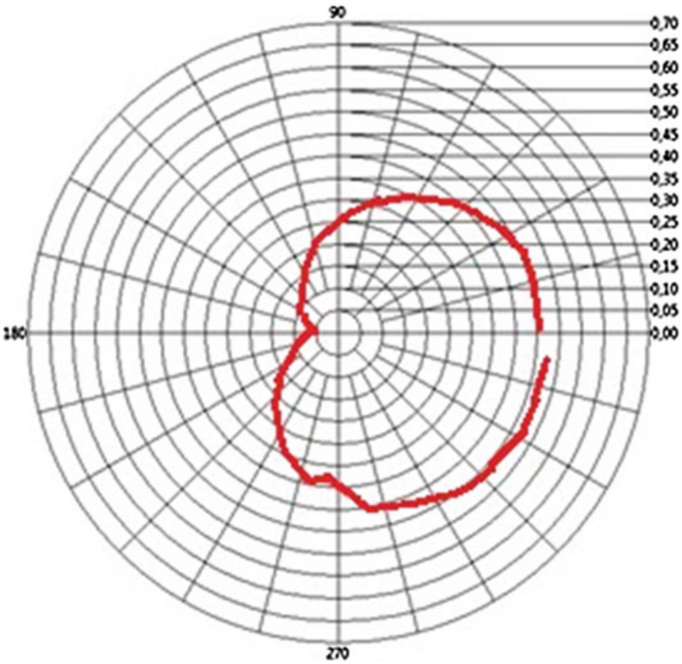

Fig. 10 The trajectory of rotor in case of blade rubbing

4 Conclusions

Failure of the middle bearing in an aircraft engine was reported. In order to reconstruct this failure, metal filings were added to the bearing's oil filter in a working engine. Tip-timing and tip-clearance analyses of seventh stage compressor rotor blades situated directly above the middle bearing were carried out. A comparative experimental analysis was also carried out on an aircraft engine with an undamaged middle bearing. Next a numerical analysis of the free vibration of a seventh stage blade was conducted to verify the experimental results. This revealed the moment that when a middle bearing starts to fail, the 7th stage blades are forced to vibrate with 1st natural frequency as seen in the Campbell diagram.

The method presented in this paper enables the prediction of middle bearing failure in an aircraft engine 33 min before it happens. The results show that variance first increases with bearing failure increase, but still before complete failure it next decreases, and stabilizes when the bearing takes on a plastic state. Tip-clearance provides information about blade eccentricity. In our experiment, however, zero tip clearance only appear towards the very end because the sampling was too small.

Acknowledgments This research has been financed from Polish Government funds for the years 2012–2014 as a development project PBS1/B4/5/2012. All numerical calculations were made at the Academic Computer Centre TASK (Gdansk, Poland).

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A Comparison Between Three Blade Tip Timing Algorithms for Estimating Synchronous Turbomachine Blade Vibration

D.H. Diamond, P.S. Heyns and A.J. Oberholster

Abstract Blade Tip Timing (BTT) is a non-intrusive condition monitoring technique used to measure blade vibration in turbomachinery. The method is suited for industrial implementation due to its low cost and ability to measure vibrations of all blades in a single blade row. The signals captured by a BTT system is however aliased which makes determining the vibration characteristics of the blades non-trivial. This article is concerned with comparing the accuracies in estimating blade vibration frequency and amplitude of three different data processing algorithms namely, the Auto-Regressive, Circumferential Fourier Fit and a new Bayesian regression approach. This is done using numerically simulated BTT data for different blade vibration conditions.

1 Introduction

Failures in rotating machinery are most often the consequence of rotating blade failures [8]. The loss of a blade can have significant economic and safety impacts. Reference [1] reports that 42 % of gas engine failures are due to blade failures.

Steam turbines are just as susceptible to blade failures. It is reported that 75 % of blade failures are low pressure (LP) blade failures. Roughly 30 % of these failures are attributed to high cycle fatigue. A more alarming statistic is that 40 % of blade failures have unknown causes. This explains why 45 % of blade failures are repeat or multiple blade failures [4].

In the same study, [4] investigates the financial implications of an unplanned LP turbine blade failure? The average production loss per failure for nuclear units is

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Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_18

2.38 and 0.68 million MW-hr for fossil fuel units. Assuming an availability factor of 85 % for turbines, the average monetary loss of production is R1600 million (152 M USD) and R460 million (44 M USD) for nuclear and fossil fuel units respectively. This prediction excludes the cost of unit reparation.

Given the negative implications of blade failures and the uncertainty with regards to blade failure mechanisms, using condition monitoring technology on turbomachines is of critical importance.

Strain gauges, being the conventional measurement technique used for turbomachinery blade vibration, have some shortcomings [13]:

- The use of strain gauges requires high quality telemetry systems for communication, which is time-consuming to install and because of this, very expensive.
- Strain gauges interfere with the mechanical and aerodynamic properties of the blade-disk assembly.
- Strain gauges have limited operating lifetimes due to exposure to harsh operating conditions.
- Usually, not all blades are instrumented with strain gauges, giving only a partial picture of the vibration response.

Blade Tip Timing (BTT) is a non-intrusive measurement technique for online measurement of turbomachinery blade vibration. BTT uses proximity probes distributed circumferentially and mounted radially through the turbomachine casing above the row of blades being measured. The Time-of-Arrival (ToA) of each blade at a proximity probe is measured and information regarding the vibrational state of the blade is determined.

Consider a turbomachinery blade that is rotating as a rigid body (i.e. in the absence of vibration). The time it arrives at a tip-timing proximity probe is then completely dependent on the shaft angular velocity, Ω. When the blade additionally undergoes vibration, the blade will arrive earlier or later at the probe based on the state of its current vibration. A Once Per Revolution (OPR) pulse is used as a shaft position reference. Figure 1 illustrates the concept behind BTT.

Based on the ToA difference between a vibrating and non-vibrating blade, the tip displacement is sampled at each proximity probe. This sampling rate is completely dependent on the shaft speed as well as the number and spacing of tip-timing probes (i.e. if the rotor is turning at 25 Hz and one has 4 proximity probes, the effective sampling rate is 100 Hz). As a result, the extracted signals are inherently subsampled (Fig. 2) and conventional signal processing techniques such as the Fast Fourier Transform (FFT) have limited use. As such, alternative algorithms need to be developed to extract blade vibration information.

There exist many of these algorithms. There is however no consensus in published literature as to which method performs the best and how accurate these methods are. The reason for this is partly because turbomachinery blade vibration is notoriously difficult to measure and thus difficult to validate.

Because of this, there is disagreement as to the applicability of BTT systems. Some statements applaud it, saying “Blade tip timing has the potential to overcome many of the limitations of currently well-established systems, providing more

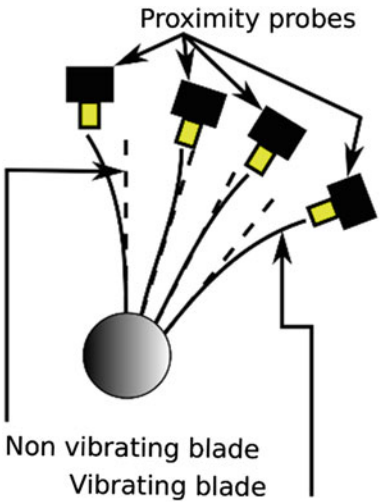

Fig. 1 Illustration of BTT principle

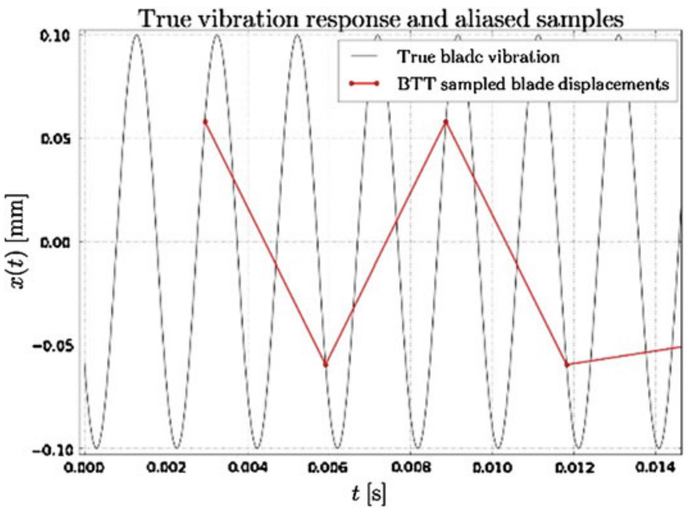

Fig. 2 Illustration of aliasing present in BTT

information at a fraction of the cost" [5]. Other authors are skeptical as to the practical applicability of BTT, saying "Unless a diagnostic technique is made simple to implement and whose reliability is proven, power plants will not find it attractive to invest on upgrade for safe operation of the machine" [11].

The purpose of this article is to compare three different BTT algorithms on simulated blade vibration data. Four different test cases will be examined to determine the accuracies of the methods under different circumstances.

2 BTT Algorithms

Synchronous blade vibration occurs when the blade vibration frequency is an integer multiple or Engine Order (EO) of the rotor speed. Synchronous vibration can be caused by a variety of structural components in the fluid flow path, like stator vanes, diaphragms, structural components and moisture separators [10]. Blades can also vibrate at a non-integer multiple of the rotor speed. This is referred to as asynchronous vibration and can occur because of flutter instabilities, rotating stall or acoustic resonance [12].

Synchronous vibration is much more difficult to measure due to the fact that a proximity probe will measure the same tip displacement for each revolution, causing multi-revolution measurements to be redundant. Measuring over multiple revolutions during asynchronous vibration increases the amount of unique data points. Among BTT algorithms one finds two main categories, namely direct and indirect methods. Direct methods operate during steady state conditions (i.e. constant rotor speed) and indirect methods during transient conditions. This article is only concerned with direct methods.

A commercial vendor of BTT systems is Hood Technology Corporation. It is reported on their website that they make use of the Circumferential Fourier Fit (CFF) method. The CFF method assumes a Single Degree of Freedom (SDoF) model for blade vibration and uses an order tracking method to infer the amplitude and phase of vibration, given the correct frequency. The frequency of vibration is often unknown, which limits the CFF method's applicability. For information as to how the method works, the reader is referred to [9].

Although Hood Technology Corporation's systems have been used widely in published literature, it is mostly used as a black box. The outputs from the system are used to perform diagnostics. No literature could be found where the inherent accuracy of the CFF method is evaluated.

Another popular technique is the Auto-Regressive (AR) family of methods. This method also assumes a SDoF model for turbine blade vibration and determines the frequency, amplitude and phase of the vibration.

In contrast to the CFF method, there exist many published investigations as to the accuracy of the AR method. In an article by Carrington et al. [2], a simulated spring-mass-damper model is excited and blade tip response is measured by a BTT system. The measured tip displacements are then subjected to varying levels of noise corruption and the vibration characteristics are then calculated. Carrington and his co-workers found that in general, the AR method is capable of determining the vibration frequency under low amounts of noise. They assumed that all the blades vibrate at the same frequency. This can be the case in a true turbine, but the presence of mistuning can influence each blades' own dynamic characteristics.

Reference [5] describe various AR based methods assuming a two DoF model for blade vibration. They used numerical experiments to illustrate the method and later on validated the methods experimentally [6]. The results confirmed that the AR method is capable of estimating the frequency and phase accurately. In his Ph. D. thesis, Grant [7] experimentally investigated the AR method to determine the frequency of gas turbine blade vibrations. He concluded that where the tip velocities of the blades were relatively low, the AR method predicted the vibration frequency with reasonable accuracy. When the tip velocities were high, the AR method failed to produce reliable results. He compared the BTT results to strain gauge data. Vibration amplitudes were not compared between BTT and strain gauge data, but only vibration frequency. The reason for this was that the strain gauge data was not accurate enough.

A new technique for inferring the vibration characteristics employs Bayesian linear regression and will henceforth be referred to as the Diamond method. This approach uses Bayesian linear regression to determine the amplitude and phase of vibration, while determining the vibration frequency by means of optimization. In a conference paper [3] the method was compared to the AR method on simple simulated vibration data. It was found that the Diamond method exhibited noise tolerant behaviour, but needed to be improved to uniquely determine the vibration frequency.

The present study will compare the three abovementioned methods based on simulated blade vibration data. Instead of using a simple sinusoid or a spring-mass-damper model to determine the vibration, a Finite Element (FE) model is employed. This is done to add some variability to the response signal that is derived from the physics of the problem.

3 Numerical Experiment

The FE model used to determine blade response is shown in Fig. 3a. The blade is 110 mm long, 60 mm wide and 2 mm thick. The material chosen in structural steel with elasticity modulus 210 GPa and density 7,900 kg/m^3. The blade is completely fixed on the bottom and on the symmetry planes. The blade is excited using periodic impulse forces of constant magnitude. The durations of the impact forces are 0.2 ms and the magnitude 1 N. The frequencies of the impulses are 124.3 Hz on one test and 513.7 Hz on another. The impulse frequencies coincide with the blade's first two natural frequencies.

By looking at Fig. 3b, it is clear that the tip displacement is not purely sinusoidal, there are harmonic contributions as well. This is a more accurate representation of blade vibration than a pure sinusoid. The response is used in a signal generator that simulates the ToA of the blade at several probes based on the shaft speed, blade radius and proximity probe placement. Two different sets of probes are used. On

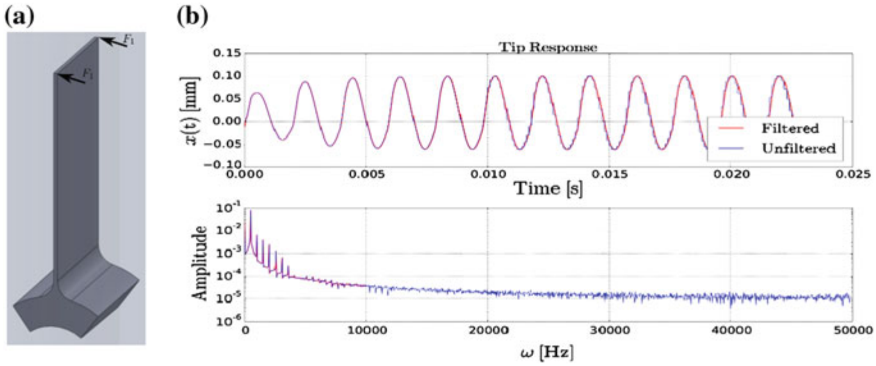

Fig. 3 **a** Turbine blade used in FE model, **b** and response of blade to periodic excitation

one set, four probes are located at circumferential positions of 10°, 20°, 30° and 40°. The second set uses four probes positioned at 10°, 18°, 33° and 40°. This was done to investigate the effect of having regularly spaced probes versus irregularly spaced probes.

The tip displacements are normalized to have maximum amplitudes of 0.1 mm. Random noise is then added to the signal. The noise is sampled from a Gaussian distribution with mean 0 and standard deviation 0.01 mm, i.e. 10 % of the amplitude. The algorithms are then used to determine the vibration frequency and amplitude. For each test case, 1,000 different simulations are considered as the noise is random.

4 Results and Discussion

The result of each test case is shown as dots on a two dimensional plane. The two reported values are amplitude estimate error (y-axis) and EO estimate (x-axis). Along with each data point, a standard deviation ellipse is drawn indicating the mean and standard deviation for each method. Two subplots are shown for each test case, where subplot (b) is a zoomed in version of subplot (a). It was mentioned earlier that two sets of probes will be used. One set has regular probe spacing and one set has irregular probe spacing. The AR, CFF and Diamond 1 results were obtained on the regularly spaced probe set. The Diamond 2 results were obtained by implementing the Diamond method on the second probe set (i.e. with irregular probe spacing at 10°, 18°, 33° and 40°).

The result for test case 1 is shown in Fig. 4. The vibration frequency is 124.3 Hz occurring at an EO of 6.

From the Fig. 4 it can be seen that all methods are able to determine the EO of vibration within relative accuracy. The AR method's Standard Deviation of the Amplitude Error (SDAE) ranges from −20 to 30 %. The Diamond 1 method has a

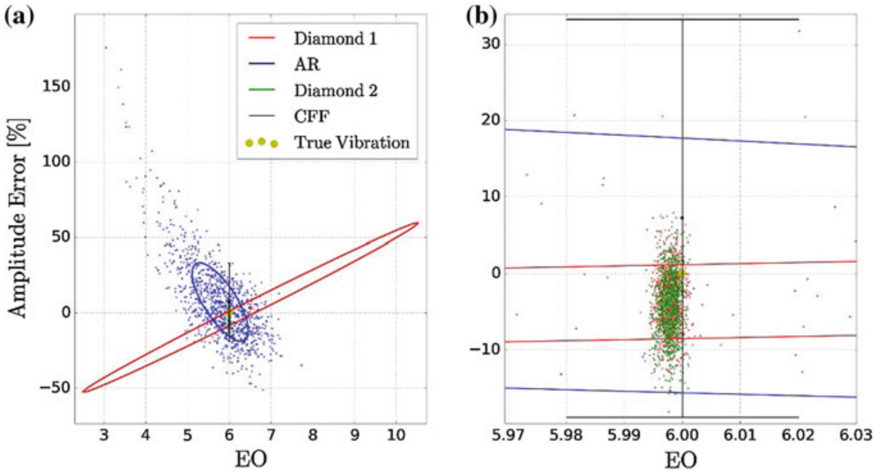

Fig. 4 Simulation results for test case 1, vibration frequency of 123.3 Hz and an EO of 6

very large SDAE. This is because of 8 outliers that are estimated to be at an EO of 38, the other 992 data points are very accurate just as all the Diamond 2 data points, exhibiting a SDAE of about −8 to −2 %. The CFF method as implemented here cannot determine the EO. The CFF method is allowed to perform all calculations with the correct EO and the resulting SDAE ranges from about −15 to 32 %.

Some important observations can be made from the data. When the Diamond 1 method succeeds in estimating the EO correctly it is very accurate. The Diamond method is however prone to incorrect estimates of EO. The AR method correctly estimates the EO on all occasions. It is however less accurate than the Diamond method in terms of amplitude estimate. The accuracy of the CFF method seems to be similar to that of the AR method. The Diamond 2 method calculates all EO’s correctly. This might indicate that using probes spaced at irregular distances is beneficial in this case. The Probe Spacing on the Resonance (PSR) ratio is a measure of how much of the vibration signal is sampled in total. If the PSR ratio is 100 %, the complete cycle is sampled. In this case the PSR ratio is 50 %, indicating only half of the vibration cycle is ‘seen’ by the proximity probes.

The result from test case 2 is shown in Fig. 5. The vibration frequency is 123.3 Hz and the EO is 12.

It can be seen from Fig. 5 that all methods produced accurate results. The AR method exhibits a SDAE between −15 and 15 %. The Diamond 1 and Diamond 2 methods show SDAEs between −1 and 6 %. The CFF method shows a SDAE between −13 and 17 %.

The test case shows that the EO of vibration makes a big difference in the accuracy of a BTT algorithm. In this case, the PSR ratios of all cases are roughly 100 %. This shows that sampling the whole vibration cycle increases algorithm accuracy.

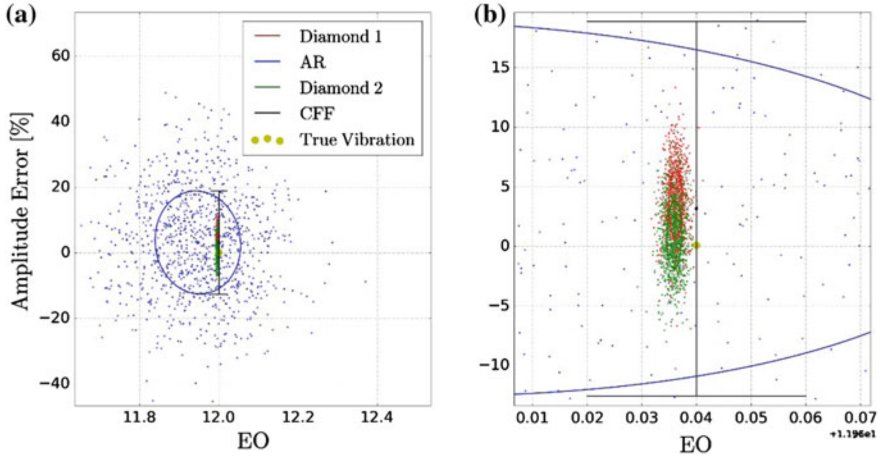

Fig. 5 Simulation results for test case 2, vibration frequency of 123.3 Hz and an EO of 12

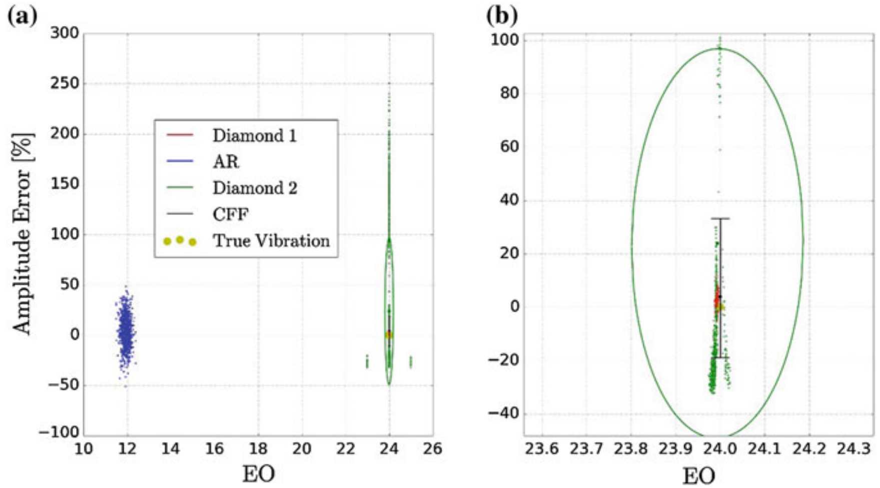

Fig. 6 Simulation results for test case 3, vibration frequency of 123.3 Hz and an EO of 24

The result from test case 3 is shown in Fig. 6. The vibration frequency is 123.3 Hz and the EO is 24.

From the Fig. 6 it can be seen that the AR method failed to recover the EO of vibration for all data points. The SDAE of the AR method ranges between −10 and 18 %. The Diamond 2 method has a very large SDAE, between −50 and 100 %. It estimates the EO incorrectly on a couple of occasions. The Diamond 1 method is very accurate with a SDAE between 0 and 5 %. The CFF method has a large SDAE, ranging between −19 and 35 %.

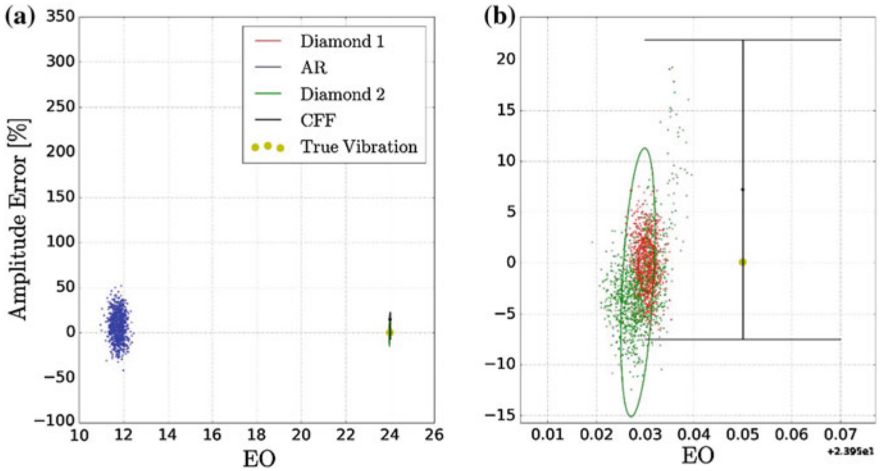

Fig. 7 Simulation results for test case 4, vibration frequency of 513.7 Hz and an EO of 24

The PSR ratio of this test is 200 %, meaning the proximity probes 'sees' two vibration cycles. The AR method is not capable of returning the correct EO for a PSR ratio over 100 %. The identified EO of 12 is exactly half of the true EO, not some random EO. More investigation into this phenomenon can help shed light onto using the AR method in cases where the PSR ratio is above 100 %. For this test case, the Diamond 1 method performs better than the Diamond 2 method. This indicates that using regularly spaced probes is beneficial for this test case, as opposed to using irregularly spaced probes.

The result from test case 4 is shown in Fig. 7. The vibration frequency is 513.7 Hz and the EO is 24. Once again it can be seen that the AR method estimates an EO of 12 instead of 24. It has a SDAE between −8 and 21 %. The CFF method has a SDAE between −7 and 22 %. The Diamond 1 and Diamond 2 methods managed to estimate the EO correctly. The Diamond 1 method has a SDAE between −3 and 3 %, this is the most accurate result of all test cases. The Diamond 2 method has a SDAE between −15 and 11 %.

It appears for this case that using probes spaced at regular distances performs better than probes spaced irregularly.

5 Conclusion

This paper set out to compare three different BTT algorithms on simulated BTT data. The AR and CFF methods are established methods used in industry. It appears that both methods have similar accuracies. The big advantage of the AR method is that it explicitly calculates the frequency of vibration. Using the AR method for a

PSR ratio higher than 100 % results in incorrect frequency estimates and additional interpretation is required for these instances.

The CFF method as implemented in this work cannot calculate the frequency of vibration. The frequency must be known beforehand, which limits the method's applicability.

The Diamond method is a new technique based on Bayesian linear regression. It was demonstrated in this work that the Diamond method is more accurate than the AR and CFF methods in most instances. The Diamond method is however prone to large frequency and amplitude estimation errors in some cases. Combining the robustness of the AR method and the accuracy of the Diamond method might solve this problem. Further investigation into this is required.

It is also observed that under certain circumstances, using proximity probes spaced regularly from one another is beneficial to the accuracy of the algorithms.

On other occasions it is better to have the probes spaces irregularly. Investigating why this happens will aid in placing the proximity probes optimally during installation.

As alluded to in the introduction, there is no consensus among published research as to how different BTT algorithms compare against one another in accuracy. The practical value of this article is to fill that knowledge gap. Two established methods, the AR and CFF methods, is compared to one another and found to be of similar accuracy, although the CFF method cannot determine the frequency of vibration. Future BTT researchers and practitioners can now make an informed decision as to which BTT algorithm to use based on the advantages and limitations concluded to in this paper. Along with this, a new method, the Diamond method, is tested and found to be promising. The BTT community now has an additional tool to address the difficulties of processing BTT data.

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Part III
Technologies and Systems

Maintenance Analysis of a System with Varying Repair Rate and Vacation Period for the Repair Facility

Venkata S.S. Yadavalli, Shagufta Abbas and Johan W. Joubert

Abstract Maintenance analysis of an n-unit warm standby system with varying repair rate and the vacation period for the repair facility is studied in this paper. This vacation period occurs after each repair completion. Also, the repair rate of a unit depends on the number of failed units at the epoch of the commencement of the repair. The life time of a unit while on line is arbitrarily distributed random variable, while in standby has a constant failure rate. Identifying suitable regeneration points, expressions for the availability, reliability and the profit function are derived. A numerical example provided to illustrate the results obtained.

Keywords Maintenance analysis · System reliability · Reliability quantification

1 Introduction

The reliability and availability of repairable systems play an important role in maintenance systems. Many of such systems in the production environment and other systems have been studied by [1–7]. References [8, 9] studied the reliability analysis or the maintenance optimization with a consideration of vacation period for the repairman for a two unit cold standby system. Subsequently, they also studied a deteriorating repairable system with a repairman having the vacation period. In practical situations the repair facility also needs to prepare itself for the next repair. We consider in this paper, with a model in which, the repair facility is not available for a random time after each repair completion.

Many n-unit systems studied in the past had the assumption that the repair rate is constant. However, Ref. [10] studied an n-unit warm standby system with varying repair rate and a single repair facility without any vacation time. It is generally assumed that repair facility will remain available every time without rest.

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_19

This motivates us to study an n-unit warm standby system with varying repair rate and the vacation period for the repair facility.

This paper contributes to the study of maintenance systems in two ways:

i. The introduction of vacation period (i.e., the vacation for the repair facility will be given just after the completion of each repair);
ii. Varying repair rate (the repair rate depends on the number of failed units).

2 Assumptions and Notations

i. The system consists of n identical units; one operates online and the others are warm standbys.
ii. There is a single repair facility and the repairs are taken up in FIFO order.
iii. The repair facility may be on vacation for some time.
iv. Each unit is new after repair.
v. Switch is perfect and switchover is instantaneous.
vi. At t = 0 there is a system recovery; i.e., system enters the upstate from the down state. This event is denoted by the symbol E.
vii. The failure rate of a unit while in standby is a constant denoted by b.
viii. The life time of a unit while online is an arbitrary distributed random variable with pdf $f(.)$.
ix. The repair rate of a failed unit is a constant which depends upon the number of failure at the epoch of commencement of a repair. If there are j failed units at the epoch of commencement of repair, the repair rate is μ_j. We also define $\mu_o = 0$, and $\mu_n = v$.
x. The vacation time for the repair facility is an exponentially distributed random variable with parameter ν.

The following notations are needed in the sequel:

Z(t) = j is state of the repair facility at a time t, if the repair rate of the unit under repair is μ_j, Z(t) = 0 implies that the repair facility (RF) is free and can see any unit for repair as and when it fails:

Z(t) = n if RF is under vacation at time t.

N(η, t) = *Number* of η events in (0, t]

R (t) = P [system is up in (0, t] | E at t = 0]

A (t) = P [system is available at t | E at t = 0]

$\lambda_i = (n - 1 - i)\, b$

© = Convolution symbol

$C^{(n)}(t)$ = n—fold convolution of the function c(t).

$C(t) = 1 - \int_0^t c(u)\,du$

Ø*(s) = Laplace Transform of an arbitrary function Ø (t).

3 The Subsystem

When one unit is continuously operating online, the behavior of the other units can be studied independently. We call the system consisting of all the units other than the one operating online and the repair facility as the subsystem. If Y(t) denotes the number of failed units at time t in the subsystem then its state at any time t can be described by the ordered pair (i, j), where Y(t) = i, Z(t) = j. If there are i failed units and repair facility is under vacation; i.e., Y(t) = i, Z(t) = n. The state space of the stochastic process describing the behavior of the subsystem is as follows:

$$\begin{aligned} \text{Let}\quad A &= A_1 U\ A_2 U\ A_3,\ \text{where} \\ A_1 &= \{(0,\ 0)\} \\ A_2 &= \{(i,\ j);\ 1 \le j \le i \le n-1\} \\ A_3 &= \{(i,\ n);\ 0 \le i \le n-1\} \end{aligned} \tag{1}$$

We note that A is the state space of the stochastic process describing the subsystem. A contains, $K = \frac{n(n+1)}{2} + 1$ elements.

Now let B be the set of positive integers less than or equal to K, we define a bijective mapping

$\pi : A \to B$ as follows

$$\pi(i,\ j\ ) = \frac{i(i-1)}{2} + j + 1 \tag{2}$$

The function $\pi^{-1}(.)$ is determined from the following rule;

$$\pi^{-1}(k) = (0, 0)\ \text{ if }\ k = 1 \tag{3}$$

If k > 1, find the smallest positive integer i such that $k \le S_i + 1$ where

$$S_i = \frac{i(i+1)}{2} \tag{4}$$

This fixes our i; then j is determined from the relation

$$j = i + k - 1 - S_i \tag{5}$$

Let, for fixed t,

$$W(t) = \pi(i,j),\ \text{if}\ Y(t) = i, Z(t) = j \tag{6}$$

Then W(t) = k implies Y(t) = i, Z(t) = j where $\pi^{-1}(k) = (i, j)$.

It is clear that the behavior of the subsystem is also described by the stochastic process {W(t), t ≥ 0}. For studying the behavior of the system we also require the following auxiliary functions, which will be considered only during the period of operation of an online unit or part thereof:

$$\begin{aligned} p_{kk'}(t) &= P[W(t) = k' \mid W(t) = k], k, k' \in B \\ P_k^T(t) &= [p_{k1}, p_{k2}, \ldots, p_{kK}] \end{aligned} \tag{7}$$

Theorem *For* $\alpha, \beta \in B$, let $\pi^{-1}(\alpha) = (i_1, j_1)$ *and* $\pi^{-1}(\beta) = (i_2, j_2)$, *then the function* $p_k(t)$ *is given by* $p_k(t) = \exp(Dt)p_k(0)$ *where* $p_k(0) = e_k$ *is the column vector whose kth element is one and all the others are zero, and* $D = [d_{\alpha\beta}]$ *is a* $K \times K$ *matrix. The elements of D are given by*

$$d_{\alpha,\alpha} = -(\lambda_{i_1} + \mu_{i_1});\ \alpha = 1, 2, 3, \ldots, K \tag{8}$$

For $\alpha \neq \beta$,

$$\begin{aligned} d_{\alpha,\beta} &= \{\lambda_{i_1} \text{if } i_2 = i_1 + 1 \text{ and } j_2 = j_1\} \\ &= \{\mu_{j_1} \text{if } i_2 = i_1 - 1 \text{ and } j_2 = \text{n or } j_1 = \text{n and } i_1 = i_2 = j_2\} \end{aligned} \tag{9}$$

Proof We observe that

$$\begin{aligned} &P[Y(t+\Delta) = i_2, Z(t+\Delta) = j_2 \mid Y(t) = i_1, Z(t) = j_1] \\ &= \lambda_{1_1}\Delta + o(\Delta) \quad \text{if } i_2 = i_1 + 1 \text{ and } j_2 = j_1, \\ &= \mu_{j_1}\Delta + o(\Delta) \quad \text{if } i_2 = i_1 - 1 \text{ and } j_2 = \text{n or } j_1 = \text{n and } i_1 = i_2 = j_2 \\ &= 1 - (\lambda_{i_1} + \mu_{j_1})\Delta + 0(\Delta) \text{ if } i_2 = i_1 \text{ and } j_2 = j_1 = o(\Delta) \end{aligned} \tag{10}$$

for other values of i_2 and j_2

For

$$\begin{aligned} &i_1 = 0 = j_1 \\ &P[Y(t + \Delta) = i_2, Z(t, t + \Delta) = j_2 \mid Y(t) = 0, Z(t) = 0] \\ &= (n-1)b + o(\Delta) \text{ if } i_2 = 1 \text{ and } j_2 = 1 \\ &= 1 - (n-1)b + o(\Delta) \text{ if } i_2 = 0 = j_2 \\ &= o(\Delta) \text{ for other valuesof } i_2 \text{ and } j_2 \end{aligned} \tag{11}$$

Using these observations and considering the behavior of the subsystem in the interval (t, t + Δ) we arrive at the following matrix differential equation:

$$\frac{d}{dt} p_k(t) = \mathrm{D}\, p_k(t) \tag{12}$$

The solution of this matrix differential equation is $p_k(t) = \exp(Dt)p_k(0)$. Having identified the subsystem, we are now in a position to analyze the main system. □

4 The Main System

The subsystem taken together with the unit operating online will be called the main system. To study its behavior, we define the following events.

E_{ij} at t: event that one unit is just online at t and Y(t+) = i, Z(t+) = j; and (Y(t+), Z(t+)) ∈ A

We also require the following auxiliary functions h (t, i′, j′ | i, j) to describe the behavior of the main system when it is in upstate.

$$\mathrm{h}\,(\mathrm{t, i', j'} \,|\, \mathrm{i, j}) = \lim_{\Delta \to 0} \Pr\,[\mathrm{E}_{i',\mathrm{j}'} \text{ in } (\mathrm{t, t} + \Delta), \text{ system is up in}(0, \mathrm{t}] \,|\, \mathrm{Eij}]/\Delta$$

Next we derive the equation satisfied by h (t, i′, j′ | i, j). For convenience we let

$$\mathrm{P(t, i', j'|i, j)} = \mathrm{p_{kk'}(t)}, \quad \text{where} \quad \mathrm{(i, j) = k} \quad \text{and} \quad \mathrm{(i', j') = k'}.$$

Observe that h (t, i′, j′ | i, j) Δ is the probability of occurrence of an $E_{i',j'}$ event in (t, t + Δ) given an E_{ij} at t = 0. Hence for the occurrence of $E_{i',j'}$ in (t, t + Δ), the unit which is operating online must fail in (t, t + Δ). This failure may be the one which was put on line at t = 0, or a subsequent one.

For all (i, j) ∈ A and (i′, j′) ∈ C, we have

$$\begin{aligned} \mathrm{h(t, i', j' \,|\, i, j)} &= \mathrm{f(t)\, p\,(t, i' - 1, j' \,|\, i, j)} \\ &\quad + \sum_{(i_2, j_2 \in C)} f(t)\mathrm{p(t,}\ i_2, j_2 \,|\, \mathrm{i, j)} \copyright\, \mathrm{h\,(t, i', j'} \,|\, i_2 + 1, j_2) \end{aligned} \tag{13}$$

$$\begin{aligned} \text{where } \mathrm{C_1} &= \{(0,0)\}, \\ \mathrm{C_2} &= \{(\mathrm{i,j});\ 1 \le \mathrm{j} \le \mathrm{I} < \mathrm{n} - 1\} \text{ and} \\ \mathrm{C_3} &= \{(\mathrm{i,n});\ 0 \le \mathrm{i} < \mathrm{n} - 1\} \text{ and} \\ \mathrm{C} &= \mathrm{C_1\, U\, C_2\, U\, C_3} \end{aligned} \tag{14}$$

For fixed (i′, j′) above equation can be solved for h* (s, i′, j′ | i, j) by Laplace transform technique.

5 Reliability of the System

We now drive an expression for the reliability R(t) of the system. Considering the mutually exclusive and exhaustive cases that the unit which was put online at t = 0

(1) Does not fail up to time (2) fails before the time t, we obtain the expression

$$\mathrm{R(t)} = \overline{F}(\mathrm{t}) + \sum_{(i,j)\in C} h(t, i, j\,|\,n-1, n) \copyright \overline{F}(\mathrm{t}) \tag{15}$$

R*(0) gives the mean time to system failure.

6 Availability of the System

While computing the expression for the availability of the system, we have to permit system downtimes also. Hence we have to introduce some new functions. Suppose that

$$\overline{\Phi}(t) = \lim_{\Delta\to 0} \Pr[E\,in\,(t, t+\Delta), N(E, t) = 0\,|\,E\,at\,t = 0]$$

And

$$\overline{\Phi}(t) = 1 - \int_0^t \emptyset(u)du.$$

The expression for Ø(t) is derived by considering the fact that the system may or may not enter the down state in (0, t)

$$\begin{aligned}\overline{\Phi}(t) = R(t) + \sum_{(i,j)\in C} h(t, i, j\,|\,n-1, n) \copyright [\sum_{k=1}^{n-1} f(t)\,p\,(t, n-1, k\,|\,i, j) \copyright e^{-\mu_k t} \\ + \mathrm{f(t)\,p\,(t, n-1, n\,|\,i, j)} \\ \copyright \{e^{-\mu_k t} + e^{-\gamma t} \copyright e^{-\mu_k t}\}]\end{aligned} \tag{16}$$

Noting that the interval (0, t] may be intercepted by an event E or not, the availability of the system is obtained as

$$\mathrm{A(t)} = \mathrm{R(t)} + \sum_{n=1}^{\infty} \emptyset^{(n)}(\mathrm{t}) \copyright \mathrm{R(t)} \tag{17}$$

The steady state availability A_∞ can be obtained from the relation

$$A_\infty = \lim_{t\to\infty} A(t) = \lim_{s\to 0} A^*(\mathrm{s})$$

From Eq. (6) we get

$$A_\infty = \frac{R^*(0)}{\overline{\Phi}^*(0)}.$$

7 Profit Analysis

In this section we calculate the profit from the system per unit time, when the system has reached the steady state.

Let 'r' be the return rate from the system when it is operable. Then the gross return from the system per unit time is $A_\infty \times r$.

Next we consider the expenditure incurred per unit time. Let 'd' be the fixed cost per unit time associated with each of the unit in the system. Then the fixed expenditure per unit time is n × d.

Since the repair rate of a unit depends on the number of failed units at the epoch of commencement of its repair, the cost incurred for a repair should also depend on the repair rate. This repair rate is likely to be different for different repairs. In order to give due weightage to this fact, we define the event E_j as follows.

E_j Event that the repair for a unit commences and the number of failed unit is 'j' where, j = 1, 2, 3,…,n.

Let $\mathrm{N}(E_j)$ be the stationary rate of the E_j events and C_j be the cost associated with its occurrence. Then the expenditure per unit time corresponding to the repairs is $C_j \times \mathrm{N}(E_j)$. The net profit function

$$\psi(n) = \mathrm{r} \cdot A_\infty - [\sum_{j=1}^{\infty} \mathrm{N}(E_j) \cdot d_j + \mathrm{n} \cdot \mathrm{d}] \tag{18}$$

To determine $\psi(n)$ it remains for us to find and expression for $N\ (E_j)$
For this purpose define,

$$\emptyset_j(\mathrm{t}) = \lim_{\Delta\to 0} \Pr[E_j\,\mathrm{in}(\mathrm{t},\,\mathrm{t}+\Delta),\,\mathrm{N(E,\,t)} = 0\,|\,\mathrm{at\,t} = 0]/\Delta$$

Note that $\emptyset_j(\mathrm{t})$ is the first order product density. To obtain an expression for $\emptyset_j(\mathrm{t})$ we make use of the following auxiliary function;

$$\begin{aligned} D^{\emptyset_j(\mathrm{t})} = {} & [1 - \delta_{j,n-1}\sum_{k=1}^{j+1} P(t,j+1,k\,|\,n-1,n)\,\mu_k + \mathrm{p(t,\,j,\,n\,|\,n} - 1,n)\gamma]\,\overline{F}(t) \\ & + \sum_{(i',j')\in C} h(t,i',j'\,|\,\mathrm{n}-1,\mathrm{n})\,©\,[(1-\delta_{j,n-1})\sum_{k=1}^{j+1} p(\mathrm{t},\,\mathrm{j}+1,k\,|\,i',j')\gamma]\,\overline{F}(\mathrm{t}) \\ & + \delta_{j1}[\{\mathrm{p\,(t,\,0,\,0\,|\,n} - 1)(\mathrm{n}-1)\,b + \mathrm{p(t,\,1,\,n\,|\,n} - 1,n)\gamma\}]\overline{F}(t) \\ & + \sum_{(i',j')\in C} h(t,i',j'\,|\,\mathrm{n}-1,\mathrm{n})\,©\,\{\mathrm{p\,(t,\,0,\,0}\,|\,i',j')(\mathrm{n}-1)\,\mathrm{b} + \mathrm{p\,(t,\,1,\,n}\,|\,i',j')\gamma\}\,\overline{F}(\mathrm{t}) \\ & + \delta_{jn}[\mathrm{p\,(t,\,n} - 1,\mathrm{n)f(t)}\,©\,\gamma\,e^{(-\gamma t)} \\ & + \sum_{(i',j')\in C} h(t,i',j'\,|\,\mathrm{n}-1,n)\,©\,\mathrm{p\,(t,\,n}-1,n\,|\,i',j')\,\mathrm{f(t)}\,©\,\gamma\,e^{-\gamma t} \end{aligned} \tag{19}$$

The above expression $D^{\emptyset_j(\mathrm{t})}$ is obtained by considering the following mutually exclusive and exhaustive cases

i. The online unit does not fail up to t
ii. The online unit fails before t

Next we drive the following expression for $\emptyset_j(\mathrm{t})$ by considering the fact that a system recovery has occurred or not in (0, t]:

$$\emptyset_j(\mathrm{t}) = D^{\emptyset_j(\mathrm{t})} + \delta_{j,n-1}\emptyset(t) + \sum_{n=1}^{\infty} \emptyset^{(n)}(\mathrm{t})\,©\,[D^{\emptyset_j(\mathrm{t})} + \delta_{j,n-1}\emptyset_j(\mathrm{t})] \tag{20}$$

The expected number of E_j events in (0, t] is given by

$$E[N_j(t)] \quad = \int_0^t \emptyset_j(\mathrm{u})\mathrm{du}.$$

The stationary rate of occurrence of E_j events is given by

$$\begin{aligned} \mathrm{E}[N_j] &= \lim_{t\to\infty} \frac{E[N_j(t)]}{t} \\ &= 1 \lim_{s\to 0} s\emptyset^*(\mathrm{s}) \\ \mathrm{E}(N_j) &= \frac{D^{\emptyset} j^*(0)}{\overline{\Phi}^*(0)} \end{aligned} \tag{21}$$

8 Particular Case

When $\mu_j = \mu$ and $\nu \to \infty$, we get the results corresponding to the system in which the repair rate of a unit is constant. In this case the model is in agreement with the model developed in [6].

9 Conclusions

We develop a mathematical model of a maintainable system in which we jointly introduced the vacation period and the varying repair rate. The system measures like reliability, availability and expected number of repairs etc. have been obtained. Using these measures the profit function has been derived analytically in steady state case. As a special case we obtained in which the results in agreement with the results obtained previously.

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A Signal Processing Approach to Overcome the Non-linearity Problem of Acoustic Emission Sensors

Tian Ran Lin, Weiliang Wu and Andy Tan

Abstract A simple and effective signal processing method is presented in this paper to overcome the inherited non-linearity problem of acoustic emission (AE) sensors in the signal analysis. In this approach, raw data measured by AE sensors are transformed into the frequency domain and then normalized by the calibrated response chart of each individual sensor provided by the manufacturer. The normalized signals are then transformed back to the time domain to enable a direct comparison of the responses measured by different sensors. The method is particularly useful for attenuation measurement and for source separation of multiple AE sources in a complex mechanical system such as a diesel engine.

1 Introduction

Acoustic emissions (AEs) are transient elastic waves produced by the rapid releasing energy caused by discontinuities or surface displacements in a material. The phenomenon was initially discovered in the early 1950s by Kaiser who observed that a material under load emits ultrasonic waves when the previous maximum applied stress is exceeded [1]. Since then, AE techniques have been adopted in many engineering applications, particularly in Non Destructive Testing (NDT) and condition monitoring. AE techniques have been successfully employed to detect crack, fracture and property change in engineering materials [2, 3], wear or leak of oil/gas pipelines and high pressure vessels [4, 5]. AEs were also utilized for the bearing defect detection [6, 7]. It was found that the AE technique is not only more effective than the conventional vibration technique in the early bearing defect detection, it can also provide indications of the defect size and thus enables the

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_20

monitoring of the degradation rate of a bearing [6]. Most recently, AE techniques have been successfully employed for condition monitoring and fault detection of rotating machinery [7–11]. For instance, AE signals were utilized to detect the mechanical events such as valve movements, fuel injection and combustion in a multi-cylinder diesel engine [8, 12]. Nevertheless, the non-linear response of AE sensors remains a challenge in the sensor calibration for a meaningful measurement. It also poses a problem in AE data analysis, particularly when multiple sensors are needed in a single application such as in Refs. [13–15]. Under such circumstances, extensive expert knowledge is required to correctly interpret the information conveyed in the AE signals, and the analysis of AE data can only be carried out in a qualitative manner. The drawback of the AE technique often attracts criticism from practitioners in the field which motivates the work presented in this study.

The accuracy of an analysis by the direct comparison of AE signals from different (un-calibrated) sensors is always questionable since each AE sensor has the inherently unique nonlinear frequency response during the manufacturing process [16]. To overcome this problem, a simple signal processing technique is developed in this paper to normalize the non-linear response of AE sensors in the frequency domain so that AE signals from different sensors as well as the AE response of a system in different frequency bands are comparable.

A detailed description of the AE signal normalization technique is presented in the next section. A raw AE signal acquired from a 4-cylinder diesel engine is used in this study to illustrate this normalization process. The technique is then employed in the analysis of the AE signals acquired from 4 AE sensors used in the condition monitoring of the diesel engine at the unload condition. The main contribution and finding from this study is summarized in the concluding remark.

2 AE Signal Normalization Approach

As discussed earlier in the Introduction, AE signals measured by different AE sensors in a same application need to be normalized for any quantitative analysis such as source identification or source localization analysis due to the inherited non-linearity of AE sensors. A simple signal normalization process is thus developed in this paper.

The original calibration charts (supplied by the manufacturer) of four Physical Acoustic Corporation (PAC) micro-30D AE sensors used in the same condition monitoring program of a diesel engine are shown in Fig. 1. According to the manufacturer, each AE sensor is calibrated based on the surface wave calibration method developed by the US National Institute of Standards and Technology [17]. The dB value shown in the charts is based on the reference value of 1 V/μbar. The unique inherited non-linearity characteristic of each AE sensor is clearly illustrated in Fig. 1. Furthermore, it is shown that the sensitivity of the AE sensors differs from one frequency to another frequency and drops substantially outside the designated resonant frequency band (0.1–0.35 MHz).

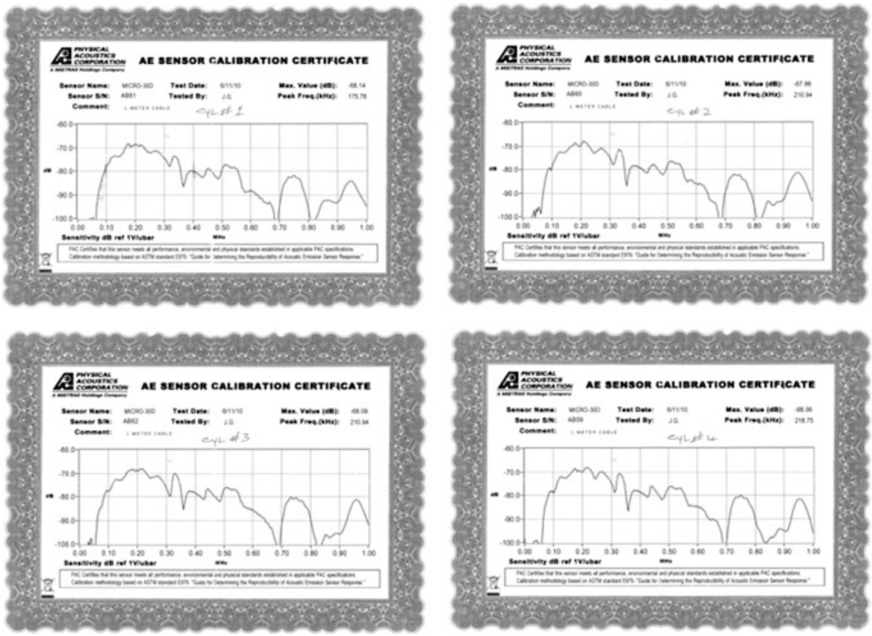

Fig. 1 The calibration charts of the four AE sensors (permission granted by Physical Acoustic Corporation)

The sensitivity of the sensors also differs from each other. The non-linearity property of AE sensors thus limits the AE technique to qualitative analysis only where care should be taken when AE responses from different sensors need to be compared.

The charts shown in Fig. 1 need to be digitized first to enable the signal normalization process of the AE data in the digital domain. The calibration chart of each sensor was scanned and digitalized at a frequency interval of 0.01 MHz on the condition that the variation of sensitivity values at the bounding frequencies (i.e., the lower and upper bound digital sampling lines) of each frequency band is less than 0.5 dB and there is smooth sensitivity value transition within the frequency band. The frequency interval of the frequency band would be further refined in the digitizing process if these conditions are not met. The averaged sensitivity of each frequency band (the averaged sensitivity value of the two bounding frequencies) is used to represent the sensitivity of the band in the AE signal normalization process. The digitized sensitivity charts of the four AE sensors used in this study are shown and compared in Fig. 2, in which the original dB scale shown in the calibration charts has been converted into the linear scale using

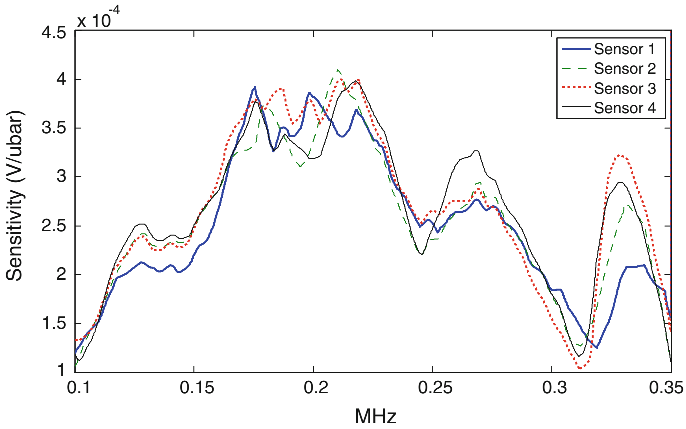

Fig. 2 The digitized calibration charts of the four sensors

$$B = 10^{\frac{A[dB]}{20}} \quad (\frac{V}{\mu bar}), \tag{1}$$

where B is the sensitivity of the AE sensor displayed in the linear scale, A is the corresponding sensitivity displayed in dB scale re 1 V/μbar.

Once the sensitivity in each narrow frequency band is determined, the measured AE signal from each sensor can be normalized by the normalization process described in Fig. 3. Four simple steps are required to transform a non-linear raw AE signal ($x(n)$) to a normalized, linear AE signal ($\bar{x}(n)$). In Step 1, a time domain raw AE data is transformed into the frequency domain ($X(k)$) using Fast Fourier Transform (FFT). This is followed by a bandpass filtering of the AE signal in the frequency domain since only the AE response within the designated working frequency band of a sensor is considered in the study. A rectangular window (i.e., a window has the value of 1 within the frequency band between 0.1 and 0.35 MHz, and 0 outside this band) is applied to the frequency spectrum to bandpass a AE signal in Step 2. Multiplying a rectangular window filter in the frequency domain is equivalent to convolute its impulse response in the time domain [18]. The impulse response of a rectangular bandpass filter $h_{BP}(m)$ which has the cut-off frequencies of ω_{c1} and ω_{c1} is given by

$$h_{BP}(m) = \frac{\sin(\omega_{c2}m) - \sin(\omega_{c1}m)}{m\pi}, \quad -\infty < m < \infty. \tag{2}$$

The use of the rectangular bandpass filter in this step is due to the consideration that a flat response of the window will not lead to amplitude distortion within the working frequency band. Nevertheless, it is worth noting that the flat rectangular bandpass

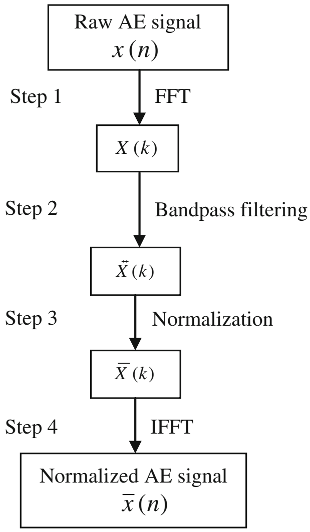

Fig. 3 A graphical description of the signal normalization process

filter is unrealizable in practical FIR filter design due to the infinite numbers of coefficients required to represent a rectangular window bandpass filter [19, 20].

In Step 3, the filtered frequency spectrum of the AE signal ($\overleftrightarrow{X}(k)$) is normalized in each narrow frequency band using the digitized calibration chart of the sensor shown in Fig. 2 to obtain the normalized spectrum ($\bar{X}(k)$). The final step of the normalization process is to inverse the normalized frequency response, $\bar{X}(k)$, back to the time domain signal using inverse Fast Fourier transform (IFFT) to have a filtered, normalized time domain AE waveform, $\bar{x}(n)$.

3 An Example of the Signal Normalization Process and Its Application to Diesel Engine Condition Monitoring Data

Figure 4 shows the in-line 4-cylinder diesel engine used in this study and the four acoustic emission sensors described in the previous section which were used to monitor the health and performance of the engine. The sensors were firmly attached onto the cylinder head of the engine block by aluminum sensor holders. The signals from the four AE sensors are recorded synchronously by a multi-channel National Instrument PXI data acquisition system with 1 MHz sampling frequency for each channel.

The raw acoustic emission signal measured by the sensor mounted close to Cylinder 1 (sensor #1) for a complete engine cycle at the unload condition is shown

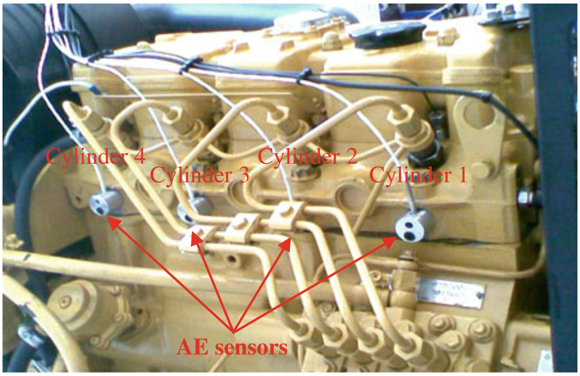

Fig. 4 A graphical illustration of the 4-cylinder diesel engine and the AE sensors used in the study

in Fig. 5a. The major AE response peaks shown in the figure can be correlated to the major mechanical events of the diesel engine (i.e., combustion, valve opening and closing) as shown in Ref. [12].

The signal normalization technique developed in this paper is applied to the AE signals measured by the sensors, (1) to overcome the inherited non-linear response problem of AE sensors, and (2) to enable a direct comparison and quantitative analysis of the AE response measured by different sensors in the time domain. The signal normalization process and its effect on the signal(s) are demonstrated by Fig. 5a–f. After the normalization, the AE signal can be displayed in the true physical unit rather than in arbitrary units or signal voltage as in the existing literatures [6, 7, 10, 12–15]. The AE response of a system in different frequency bands can also be analyzed quantitatively in the frequency domain after the normalization.

Figure 6 compares the AE RMS (Root Mean Square) energies of the signals acquired by the four AE sensors (such as that shown in Fig. 5a at the unload condition of the diesel engine. Clear energy attenuation trend is observed for AE events originated from Cylinders 1 and 4 such as IVC1, COMB1 and IVC4 marked in the figure. This is because that wave propagation of AE sources generated from these two cylinders is less affected by the wave reflection and refraction at the boundaries of the engine block as the two cylinders are the outer cylinders of the engine (see Fig. 4). For instance, the AE energy decays along the propagation path away from the source cylinder for sources originated from these two cylinders and is demonstrated by the decreasing signal amplitude of the sensors proportional to their distance from the source. On the contrary, the energy decaying trend is not so obvious for the AE sources originated from Cylinders 2 and 3 such as IVC2 and IVC3 in Fig. 6. This interesting phenomenon is caused by the sensor proximity of a small engine and the strong interference from the boundary reflection and wave refraction. Thus, the AE amplitude detected by an adjacent sensor next to the sensor

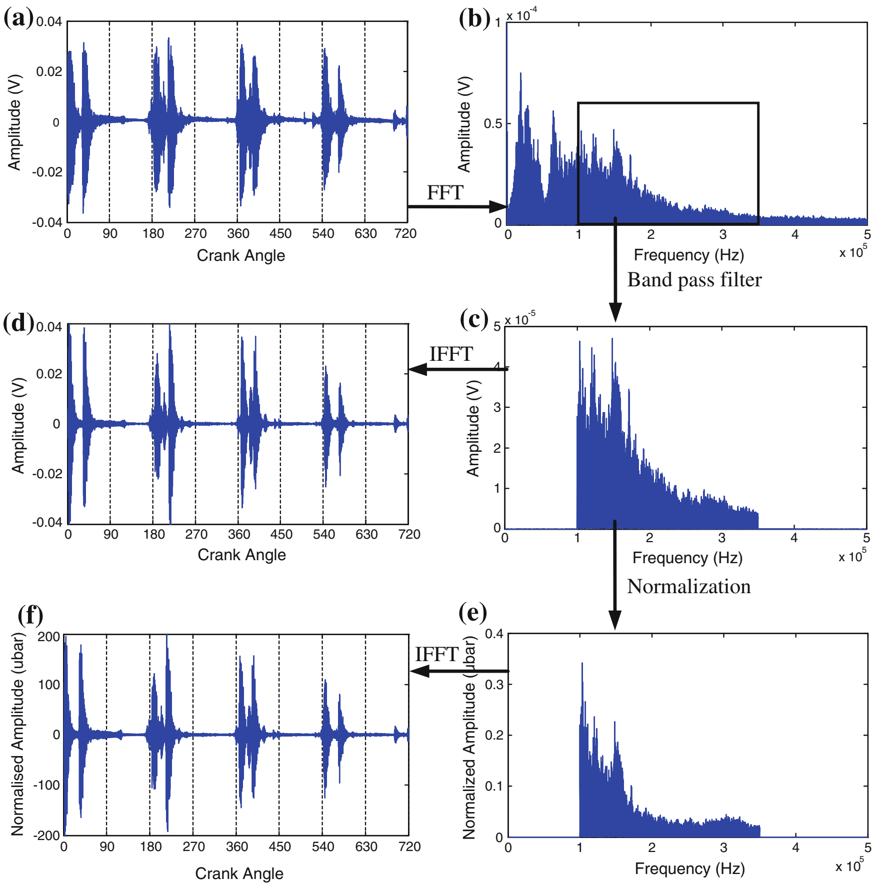

Fig. 5 The signal normalization of an un-calibrated non-linear AE signal; **a** original signal; **b** frequency spectrum of the raw signal; **c** band-passed frequency spectrum, **d** the time waveform of the band-passed spectrum, **e** normalized frequency spectrum, and **f** normalized time waveform

mounted close to the source cylinder could have similar or even higher amplitude than the latter sensor. This helps to explain why the energy decaying trend for AE sources originated from Cylinders 2 and 3 is not as clear as the AE sources originated from Cylinders 1 and 4.

The normalization process developed in this paper has also laid the foundation for the use of multiple AE sensors in real world industry applications such as source identification of multiple AE signals of complex systems [13–15] and blind source separation of multiple AE sources in diesel engines. Utilization of the normalization technique in blind source separation application of multiple AE sources of a diesel engine will be presented separately in a coming paper.

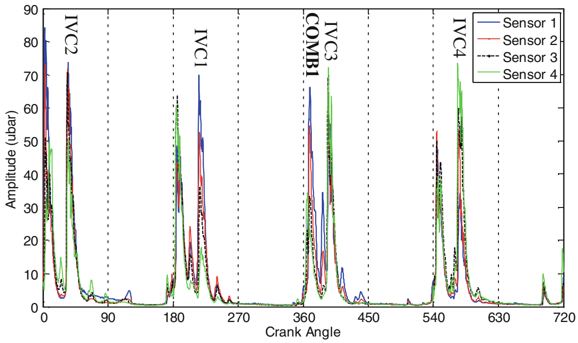

Fig. 6 Comparison of the normalized AE responses from the 4 AE sensors on the diesel engine at the unload condition. *Note* COMB1 represents the engine combustion of Cylinder 1, IVC1, 2, 3 and 4 denotes the inlet valve closing of Cylinder 1, 2, 3 and 4 respectively

4 Concluding Remarks

A simple signal processing technique is presented in this paper to overcome the long existing non-linearity problem of acoustic emission (AE) sensors which has thus far prevented the wide application of the AE technique. The four-step signal processing technique is easy to implement in the practical AE signal analysis. The process can transform a non-linear voltage AE signal to a linear true physical response of a mechanical system based on the pre-calibrated chart from the sensor manufacturer(s). The technique can also be employed for condition monitoring applications of a complex system where multiple AE sources produced by the system needs to be separated and identified.

The application of the technique was exemplified in the paper by the AE signals acquired from the condition monitoring program of a diesel engine using multiple AE sensors. The normalized AE RMS data from the 4 AE sensors at the engine unload condition were compared in the signal analysis. It was found that clear AE energy decaying trend can be observed from AE events originated from the two outer cylinders of the 4-cylinder diesel engine. On the contrary, the energy decaying trend of the AE events originated from the two inner cylinders is not clearly shown due to the strong interference from the boundary reflection and wave refraction owning to the small engine size used in the study and the complexity of the engine block.

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A New Method for Reliability Allocation: Critical Flow Method

A. Silvestri, D. Falcone, G. Di Bona, A. Forcina, C. Cerbaso and V. Duraccio

Abstract A complex system consists of many subsystems, which are developed concurrently and sometimes independently. It would be too late to validate the system reliability until the final system prototype is ready after months or years of development. From a project management point of view, the reliability of each subsystem or sub-function should be examined as early as possible. Therefore, the allocation of a reasonable reliability requirement to each subsystem and sub-function based on the system reliability target is very important. The present work analyses, in literature, the main reliability allocation techniques. Starting from the known methodologies, a new critical flow method for reliability allocation method has been developed. The proposed method can be used for complex system with serial and parallel configurations.

Keywords System reliability · Reliability analysis · Critical flow method

1 Introduction

The reliability of a complex system is the probability that the system works without failures, more or less dangerous, relating to a defined time interval. Therefore to value the reliability of a system means to value numerically its behaviour: a greater reliability relating to a particular time means a greater probability that the system works up to that time. Instead, *reliability allocation techniques* follow a different approach. We establish a global target of reliability and, according to a top-down approach, we design components in order to guarantee the above target.

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_21

So, in the present work a new method for allocating reliability has been developed. The present work analyses, in literature, the principal procedures and techniques of reliability allocation. The different methodologies can be used together; it is often possible to use more techniques in the different phases of a complex system project. The allocation procedure is an iterative one, it starts from the initial design step, when few data about components are available. In this phase, it is better to consider the sub-systems in series and to adopt one of the allocation methodologies for such systems (*Base method, Boyd method*). Then, when more data are available (number of components and their interconnections), it is possible to use other methodologies (*Agree method, Cost method, Karmiol method* (*factors product*), *Karmiol method* (*weighted factors sum*), *Bracha method, Integrated Factors Method*), that determine the allocation of reliability parameters using different factors (the system criticality and technology, the mission time, etc.).

The proposed method wants to supply logic for the analysis of prototype complex systems (serial and parallel configurations) during the pre-design phase, even if it presents general characteristics that allow extension of such logic to different design phases.

2 State of the Art: The Reliability Allocation Methods

A reliability allocation methodology starts defining all or some of the following elements [1, 15, 16]:

i. system and troubles (fundamental and not influential units, failures);
ii. system reliability parameters (system reliability target);
iii. feasibility of the system reliability target (comparison with similar systems);
iv. unit technology (mean fault rate);
v. relation between the unit fault and the system fault (series, modified, redundant, multi-modal systems);
vi. unit importance (relation between the system failure and the unit failure);
vii. modal design adequacy (relation between the mission success probability and the modal efficiency);
viii. operation cycles (operation time).

The starting point is the system reliability target, definable directly or through the following factors [11]:

- *System Efficiency* $S^*(T)$: probability that the system will satisfy a fixed operative request, working for t hours, under fixed conditions.
- *System Reliability* $R^*(T)$: probability that the system will realize perfectly the designed functions for t hours, under fixed conditions.
- *System Design Adequacy* D_S: probability that the execution of the expected designed functions will realise the mission success.

- *Operational Readiness* P_{OR}: probability that in every moment the system will be working rightly or be able to act, under fixed conditions.

$$S^*(T) = R^*(T) \cdot D_S \cdot P_{OR} \quad (1)$$

Starting from the system target, it is necessary to define reliability characteristics of the components: mean fault rates, mean lives or reliability for an established time period.

The system reliability allocation to the units, involves the resolution of the following inequality:

$$f(R_1{}^{\circ}, R_2{}^{\circ}, \ldots, R_N{}^{\circ}) \geq R^* \quad (2)$$

$R_j{}^{\circ}$ allocated reliability to unit_j;
$R*$ system reliability target;

2.1 Base Method

The base method considers the system units in series.

$$(R_1(t) \cdot R_2(t) \cdot \cdots \cdot R_N(t)) = R(t) \quad (3)$$

$R_j(t)$ unit_j reliability for t operative hours;
$R(t)$ system reliability for t operative hours.

The Base method allocates the reliability through the weight factor $W_j = \lambda_j / \sum_{k=1,\ldots,N} \lambda_k$, based on the fault rates of similar units.

2.2 Boyd Method (Equal Method and Arinc Method)

The Boyd method [2] represents an integration of the Equal method and the ARINC one for systems in series. The method proposes the following formula:

$$\lambda_{ai} = M \cdot K \cdot \lambda_{rS} \cdot 1/N + (1 - K) \cdot \lambda_{rS} \cdot \lambda_{pi}/\lambda pS \quad (4)$$

K values between 0 (ARINC) and 1 (Equal);
M safety factor = [1 − (%margin/100)].

2.3 Agree Method

The AGREE method was born in electronic field and it pays attention to the relations between unit faults and system faults. The fault rate allocated is given by:

$$\lambda_j^\circ = n_j[-\ln R^*(t)]/(N \cdot E_j \cdot t_j) \quad (5)$$

n_j unit$_\mathrm{j}$ number of modules;
N system total number of modules;
E_j unit$_\mathrm{j}$ factor of importance;
t_j unit$_\mathrm{j}$ number of operative hours.

2.4 Cost Method

Some methods propose a reliability allocation based on economic considerations. Using Lagrange multipliers, the method researchs the minimum cost function:

$$C(R^*) = C(R1^\circ) + C(R2^\circ) + \cdots + C(RN^\circ) \quad (6)$$

$C(R^*)$ cost needed to obtain the system reliability target;
$C(R_j^\circ)$ cost needed to obtain the unit$_\mathrm{j}$ reliability target.

2.5 Karmiol Method—Factors Product and Weighted Factors Sum

This method appreciates the influence of different factors for each sub-system:

- *Complexity* (Cx): it considers the number of functions;
- *State of art-technology* (A): it considers the engineering progress;
- *Operative profile* (O): it considers the mission time and the operative severity;
- *Criticality* (Cr): it considers the influence of the sub-system on the system mission success (greater criticality, greater allocated reliability).

The values of the above factors are between 1 and 10.

Karmiol Factors product: the product of the four factors represents the *effect factor* (n) for each sub-system:

$$n = Cx \cdot A \cdot O \cdot Cr \tag{7}$$

The allocated reliability value to the sub-system is:

$$R_k = R^A x\, R^B \tag{8}$$

$$A = (n_1 + n_2 + \cdots + n_m)/(2\, x\, N\, x\, n_k) \tag{9}$$

$$B = F_k/[2\, x\, (F_1 + F_2 + \cdots + F_m)] \tag{10}$$

$$N = \sum_{i=1,\ldots,m} (n_1 + n_2 + \cdots + n_m)/n_i \tag{11}$$

n_k effect factor for the subsystem_k;
F_k functions (operations) number for the subsystem_k.

Karmiol weight factors sum: the total weight factors, calculated for each subsystem_i (Ti), are added to obtain the system total weight factor (TS):

$$Ti = Cxi + Ai + Oi + Cri \Rightarrow TS = \sum_i Ti \tag{12}$$

We fix the system unreliability, then we can allocate the unreliability (and then the reliability and the fault rate) to each sub-system, through the relative weight factor:

$$W_i = T_i/T_S \tag{13}$$

2.6 Bracha Method

The method requires the determination of the following four weight factors for each sub-system:

- *State of the art-technology* (A): it considers the engineering progress;
- *Complexity* (C): it considers the sub-system number of parts:

$$C = 1 - \text{Exp}[-Kb + 0.6(Kp)] \tag{14}$$

K_b ratio between the number of components of the considered subsystem and of the whole system;
K_p ratio between the number of redundant components of the considered subsystem and of the whole system.

- *Environmental conditions* (*E*): it considers the operative severity:

$$E = 1 - 1/f \tag{15}$$

f external stress (0: min stress; 100: max stress)

- *Operation time* (*T*): it considers the operation time:

$$T = Tm/Tu \tag{16}$$

Tm system mission total time;
Tu subsystem operative time.

Then, it is possible to calculate the I_i index and the W_i weight factor, for the sub-level$_i$ (n: number of sublevels in series):

$$I_i = A_i \cdot (C_i + E_i + T_i) \tag{17}$$

$$W_i = I_i \Big/ \sum_{j=1,\ldots,n} I_j \tag{18}$$

2.7 Integrated Factors Method

The new methodology has been developed for prototype systems in series [3, 8, 9]. We have chosen the following factors and relative indexes for each sub-system:

- *Criticality index* (*C*): ratio between the number of sub-system functions that cause an undesirable event, and the number of total system functions;
- *Functionality index* (*F*): ratio between the number of total unit functions, and the number of total system functions;
- *Complexity index* (*K*): ratio between the number of unit parts and the number of whole system parts;
- *Effectiveness index* (*O*): ratio between the unit effectiveness time and the mission total time.
- *Technology index* (*S*): S = 0.5: traditional components S = 1: innovative components.
- *Electronic Functionality index* (*E*): E = 1 completely electronic system E = 0.1 completely mechanical system.

Finally, we have introduced an increase (*M*) for the *Effectiveness index* (*O*), caused by a greater operative severity. The *Global index* (*IG*) becomes:

$$IG_i = (K_i \cdot F_i \cdot S_i \cdot O_i \cdot M_i)/C_i \cdot E_i; \tag{19}$$

$$IG\%_i = IG_i \bigg/ \left(\sum_{j=1,\ldots,n} IG_i \right) \tag{20}$$

At the numerator there are those factors whose growth causes an unreliability increase, at the denominator those factors that cause a reduction. Then it is possible to allocate the system unreliability target ($U(t)$) to the unit_{i}

$$U_i(t) \; = \; U(t) \cdot IG\%_i \tag{21}$$

3 Comparison of Methods

For each method, there are some advantages and disadvantages (see Table 1). We have started from these analyses to define the new proposed approach [12–14].

4 Critical Flow Method (C.F.M)

The guidelines for the development of a proper allocation method can be summarized in the following four points:

- generality;
- standardization of input data;
- economy;
- definition of realistic and achievable requirements.

The new allocation methodology developed has been called "Method of Critical Flows". This new reliability allocation method wants to be a methodology "ad hoc" for the system examined, but it can also be extended to any complex system (series and parallel) [19].

The starting point was the analysis only of significant units, according to experience. This is an indispensable indication to explain the so-called "buffer effect" (elements in parallel). The choice to limit the analysis to a very low number of elements, depending on the particular top event, has led to less dispersed results, creating a scale of criticality and identifying priorities and hierarchies.

The previous analysis of the other methods, showed the need to use appropriate factors of influence to discriminate among the different system units. The factors chosen were as follows:

Criticality—Index C: it permits to estimate the effects on a top event caused by a total or partial failure of a single unit. The factor allocates higher reliability to less critical systems. Its range is between 0 (ideally) for a low criticality of the unit and 1

Table 1 Advantages/disadvantages of the analyzed methods

Method	Advantages	Disadvantages
BASE	• Application simplicity • Objectivity	• Only applicable to systems in series • Only applicable in the initial phases • Fault rate knowledge of similar systems
BOYD (EQUAL and ARINC)	• Versatility	• Only applicable to systems in series • Only applicable in the initial phases
AGREE	• Good detail	• Only applicable to systems in series • Applicable in advanced phase • Partial subjectivity of the analyst
COST	• Economic guide lines	• Complex or approximated analytical treatment
KARMIOL • Factors product	• Very good detail • Applicable to innovative systems • Applicable in every phase	• Subjectivity of the analyst
KARMIOL • Factors sum	• Very good detail • Applicable to innovative systems	• Only applicable to systems in series • Subjectivity of the analyst
BRACHA	• Exact analytical treatment	• Not easy determination of stress factors • Component criticality not considered
I.F.M.	• Big number of factors to guarantee the method applicability to a wide variety of systems	• Only applicable to systems in series

for absolutely critical items. The criticality index is evaluated through the following ratio:

$$C = \frac{1}{n} \tag{22}$$

where "n" is the number of "buffer elements" that can oppose a risk implementation (parallel configuration).

State of the art—Index A: it is the technological level of a unit. The factor allocates higher reliability to the most technologically advanced elements. Its range is between 0 (ideally) for old design elements and 1 for newly developed units. In this case, we estimated A = 0.5 for all units, depending on their middle technological level.

Complexity—Index K: it evaluates the complexity of the units, in terms of structure, assembly and interactions. The factor allocates higher reliability to less complex elements. We introduced three different levels of subsystem complexity, with three numerical values associated (Table 2).

Table 2 Subsystem complexity values

Value	Subsystem
0.33	Not complex subsystem
0.66	Normal complexity
1	Complex subsystem

Table 3 Values for severity of environmental conditions

Value	Subsystem
0.33	Easy operative conditions
0.66	Normal operative conditions
1	Difficult operative conditions

Running Time—Index T: it values the operating time of a unit in comparison with the total time of the mission. The factor allocates higher reliability to units working for a lower average time. It is defined as the ratio between the average operation time of each single element and the average time of the mission. For each unit the index T is given by following ratio:

$$T = \frac{T_u}{T_s} \tag{23}$$

Operation Profile—Index O: it is representative of operating conditions, in terms of working stress. The factor associates more reliability to those elements working in less difficult environmental conditions. We introduced three different levels for severity of environmental conditions, with three different numerical values associated as in Table 3:

After the above evaluations, thanks to expert judgement, it is possible to determine the Global Index (GI) for the reliability allocation of the system, defined as follows [6, 7, 10]:

$$GI_i = \frac{C_i \cdot T_i \cdot K_i \cdot O_i}{A_i} \tag{24}$$

where GI_i is the Global Index of the specific unit of the system.

This method considers now calculating the GI weight of each unit, according to the following equation:

$$W_i = \frac{IG_i}{\sum_{j=1}^{n} IG_j} \tag{25}$$

where W_i is the global weight of the i-th unit, compared to the indexes of other units and n is the number of analyzed units.

After the evaluation of the global index for each unit, it is possible to allocate the system reliability target:

$$R_i(t) = R(t)^{W_i} \quad (26)$$

that decreases when W_i increases [4, 5].

In the near future, the new proposed method will be applied, and both validated, to complex systems [17, 18], in particular to a toroidal machine, necessary to carry out research on plasma physics and controlled thermonuclear fusion [7].

The thermonuclear fusion is a strongly energetic reaction, whose operating principle, very simply, is behind the production of energy by stars: two atoms "light" (low atomic number), such as hydrogen or its isotopes deuterium and tritium, are fused to produce heavier atoms like helium. Normally a nucleus of deuterium and one of tritium are fused together in order to produce a nucleus of helium (alpha particle) and a neutron. In order to obtain the energy production through controlled thermonuclear fusion, it is necessary to heat a plasma of deuterium–tritium up to very high temperatures (about 10^8 °C), keeping the hot plasma confined in a magnetic field, able to force particles to follow spiral trajectories, away from the container walls (*magnetic confinement*).

In magnetic confinement fusion hot plasma is enclosed inside a vacuum chamber. There are two different magnetic configurations:

- Mirror configuration;
- Toroidal symmetry configuration.

Today, the better configuration is the toroidal one (Fig. 1). In this case, the toroidal magnetic field is produced by copper coils positioned around a cavity in the centre.

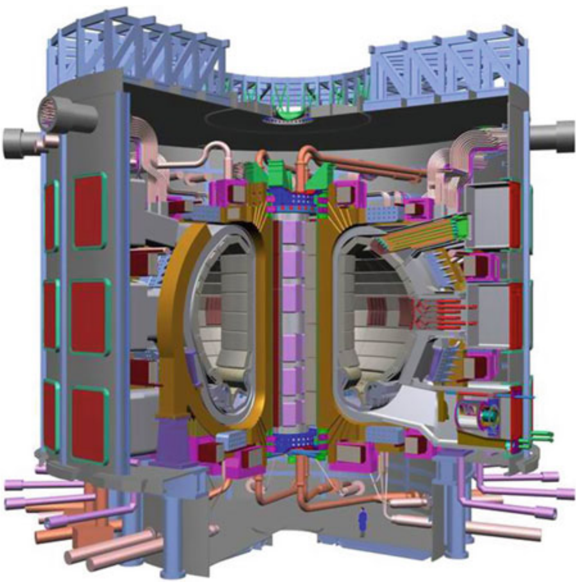

Fig. 1 Toroidal machine

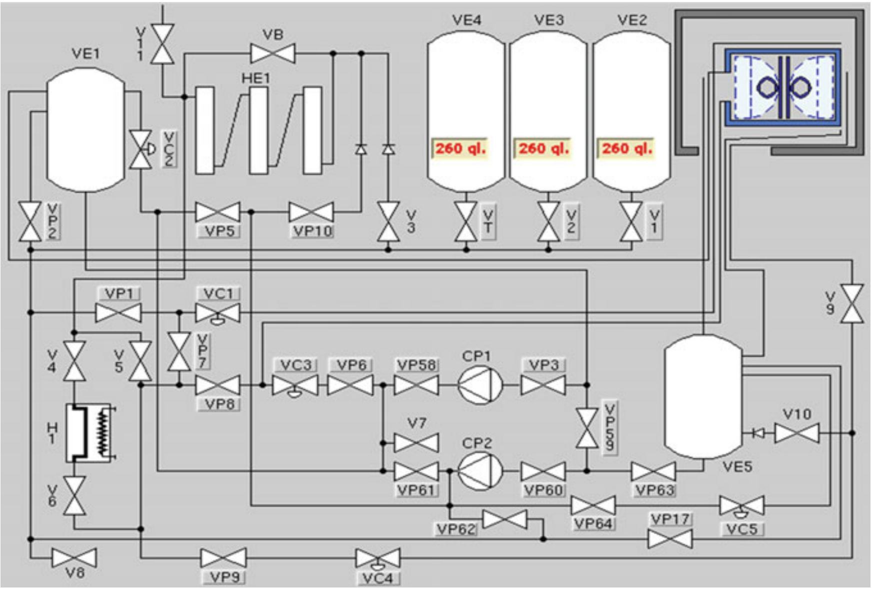

Fig. 2 Cooling system

The generation of a high magnetic field inside the chamber is due to a current of 37.8 kA for a period of about 1.5 s. Therefore it is necessary to cool the vacuum chamber and coils through a closed circuit of liquid nitrogen, characterized by (Fig. 2):

- Three storage tanks of liquid nitrogen, total capacity of 90.000 L, pressure of 2.5 bar;
- Two cryogenic pumps, lubricated by the same liquid nitrogen, delivery of about 30 m^3/h;
- Two evaporators;
- Tanks, valves and typical accessories.

The nitrogen pipes reach the cryostat, the main component of the plant, containing the toroidal system, covered by a polymeric material. Inside the cryostat, pressure is bigger than outside (20 mm H_2O), in order to avoid the possibility of entry of atmospheric air, in case of sealing problems at the equatorial doors. In fact the air humidity freezes and forms dangerous layers of ice (work temperature of −190°C). The mission of the cooling system is to guarantee correct environmental operating conditions of the toroidal machine. Initially, the copper coils are cooled up to a temperature of −190 °C, needed to have specific values of resistivity and consequently high currents (37.8 kA), required to produce the magnetic fields

Table 4 Units of cooling system

Unit 1. Manual valves	Unit 11. Cryostat
Unit 2. Safety valves	Unit 12. Liquid nitrogen tanks
Unit 3. Restraint valves	Unit 13. Separation tank
Unit 4. On-off valves	Unit 14. Collection tank
Unit 5. Solenoid valves	Unit 15. Main evaporators
Unit 6. Breaking discs	Unit 16. Secondary evaporators
Unit 7. Pressure valves	Unit 17. Heater
Unit 8. Self-regulation valves	Unit 18. Cryogenic pumps
Unit 9. Pressure-regulation valves	Unit 19. Compressed air system
Unit 10. Level valves	Unit 20. Measure modules

necessary for plasma confinement. Through a reliability block diagram (RBD), we have divided the whole system into functional blocks in series, in order to realize the reliability analysis. The identified units are (Table 4).

5 Conclusions

The proposed method wants to integrate the advantages of the previously analysed techniques (from Base Method to Integrated Factors Method). In particular CFM method uses a big number of factors in order to let the method applicability to serial and parallel configurations. The chosen standard input is the unit unreliability. The cheapness of the method is the simplicity of the analytical treatment. The principal characteristics are:

- index values are between 0 and 1 (modular structure and dynamism);
- it is possible to eliminate not influential aspects putting the relative index equal to 1;
- it is possible to introduce, if necessary, other indexes, to consider other allocation characteristics.

All in all, the proposed method is able to adapt the available methodologies to the different design phases, this is a fundamental requirement for reliability analyses.

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Design Considerations for Engineering Asset Management Systems

Florian Urmetzer, Ajith Kumar Parlikad, Chris Pearson and Andy Neely

Abstract This paper presents the key considerations to improve approaches to the design of asset management systems. Currently accepted definitions and guidance for the design asset management systems seemingly takes a monolithic approach and is more relevant when all asset management activities lie within the four walls of a single organization. In practice, it is often seen that the management of assets are done by a number of disparate organisations. In such a context, alignment of KPIs and visibility of value-drivers between the asset management systems of these organisations are critical to ensuring that all parties in the “eco-system” benefit from the assets.

Keywords Asset management systems · Asset management performance · Asset management standards

1 Introduction

This paper outlines the key design considerations to improve approaches to the design of the asset management systems needed for effective service delivery [1, 2]. The recently published ISO 55000:2014 standard for asset management defines an asset management system (AMS) as “…aset of interrelated or interacting elements to establish asset management policy, asset management objectives and processes to achieve those objectives [3].” A simplified illustration of an asset management system as defined in ISO 5500x is shown in Fig. 1.

Prior to the publication of ISO 55000, the BSI PAS 55 [4] standard mentions the need for organisations to have an effective asset management system, but does not provide any details regarding how such a system should be designed or implemented.

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_22

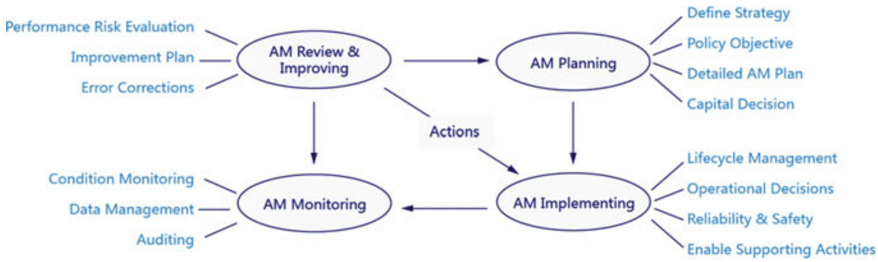

Fig. 1 A simplified "Plan-Do-Check-Act" illustration of an AMS

It is evident from these standards and best practice guides that the asset management system plays a critical role in organisations' ability to generate value from their assets. Given this importance, it is surprising that there is very little literature from academia on asset management systems, in particular about the design of these systems.

ISO 55002 addresses some of the shortcomings in the understanding of AMS by providing guidance on the implementation of an AMS. Recently, El-Akruti et al. [5] reviewed existing literature in asset management and reconstructed a strategic framework aimed at illustrating the detailed relationships and mechanisms between each specific asset management process and activity. An asset management system should fit it with the organisation's strategy, objectives, and policies. The AMS should define the asset management policy, which describes the overall approach to how assets will be managed within the organization [6]. Following this the organization should define specific, measurable, achievable, realistic and time-bound asset management objectives; and a clear plan (with specific responsibilities) to achieve those objectives. Figure 2 presents the key elements of an asset management system as defined by the Institute of Asset Management.

Although unintentional, the definitions and the above illustrations lead one to the belief that an asset management system is seen to be monolithic, and lies within the four walls of an organization. In practice, it is often seen that the management of assets are done by a number of organizations. For example, in the rail sector in the UK, the trains are operated by the train operating companies (e.g., Virgin Rail, Southwest Trains), the trains are owned by a different set of companies (e.g. HSBC Rail), and they are often maintained by the OEMS (e.g., Hitachi Rail [7]). In such scenarios, it is not clear how existing definitions and guidelines should be implemented across the different organizations that derive value from the assets (trains in the rail sector). Evidently, each organization should have an asset management system that aligns with their own objectives that aims to extract maximum value from the assets. However, these objectives are often conflicting—so the question is "how can such a disparate set of asset management systems be designed so that the whole eco-system (or value chain) can benefit from the assets?"

This paper attempts to take the first step towards answering the above question by providing some key considerations during the design or improvement of asset

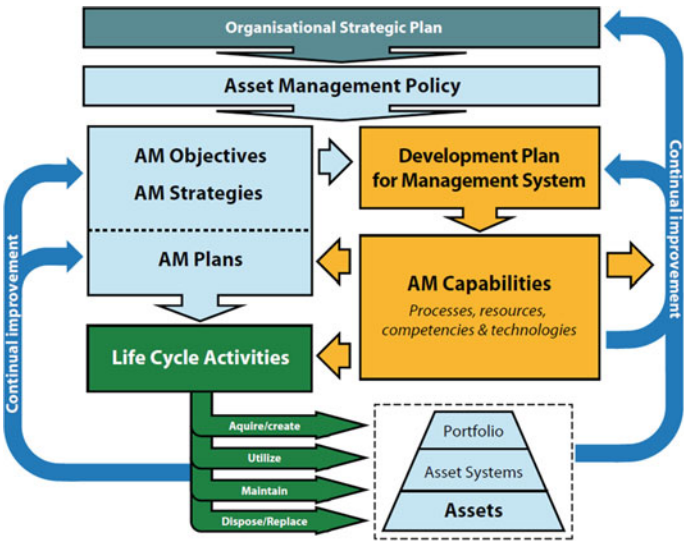

Fig. 2 Key elements of an asset management system

management systems. The structure of the paper is as follows. In Sect. 2, we briefly discuss the approach taken for this research. Following this, we present the design considerations in Sect. 3. Section 4 summarizes the key conclusions of the paper.

2 Research Approach

This study focused on examining industrial practices in designing and improving asset management systems. The activities that informed this paper consisted of a series of interviews with asset managers in companies (see Table 1) across a variety industry sectors ranging from aviation, facilities management, utilities, heavy equipment, consulting etc. These interviews aimed at understanding

i. their asset management practices,
ii. the process they use for designing and improving their asset management systems; and
iii. the shortcomings of these processes and their implications.

Interviews followed an semi structured approach, however because of the large different approaches of companies, e.g. one company did not have an overview of the status and usage of their assets, and others had to follow heavy regulations for provenance of maintenance and fulfilment of maintenance schedule, there were only high level similarities and the asset management system design described by the interviewees as well as the actual process applied was at times very varied.

Table 1 Case study companies

	Industry description	Business description
1	Defence industry	Supply of servicing and maintenance of aircrafts and attachment. Baseline is a complex servicing contract by which payment is only given when the airplane is ready to fly
2	Electrical power supplier	Long standing servicing contract of large machinery which produces power for a national power grid. Payment is based on uptime of the material, hence a lot of the services has to be done based on idealised maintenance schedules to guaranteed uptime
3	Enterprise asset management consulting	Services and support contracting on designing and implantation of asset management systems
4	Maintenance of large estate	A department servicing and maintaining buildings and assets of a large education provider. Most buildings are “A listed” (heritage relevant buildings)
5	Building and maintenance	Provider of national level building contracts with a large fleet of heavy machinery (e.g. trucks, lorries, diggers etc.)
6	Monitoring and servicing of heavy machinery fleets	Offering servicing of heavy machinery (e.g. trucks and diggers) additionally they have a heavy machinery monitoring system in place

In general the interviews conducted for this research study revealed that there is a spectrum of approaches in organisations when it comes to Asset Management Design, but the common factor (unsurprisingly) was that the approach is usually driven by the market rather than by a pre-defined design approach. It was noticed that the value of the asset is mostly defined not by a lifetime view of a single asset, but if market conditions are favourable, then asset will be retired, or in many cases exchanged against new machines. Interestingly, in some companies, there was not even any tracking of assets involved in servicing or being serviced by the company.

The detailed findings from each case study will be described in a full journal version of this paper. Here, we focus on presenting the critical factors that affected the success of the asset management system—with a view that consideration of these factors during design or improvement will ensure that the various companies that form the “asset management ecosystem” will be able to extract value from the assets.

3 AMS Design Considerations

The most interesting finding from the case studies is that the organisations examined do not have clearly defined or understood approach to “design” their asset management system. They see their AMS as not an outcome of a concerted design effort, but a system that has evolved over a number of years through external (e.g. customer requirements) and internal (e.g. organizational strategies) influences and market forces (e.g. competition, regulation). However, a common factor is that all the companies continuously strive to improve their existing systems for managing assets.

We will now discuss the key lessons learned about what needs to be considered when designing an asset management system for services. Additionally these are seen as strategically important steps to be taken to upgrade or improve existing asset management systems.

3.1 Risk and Scenario Analysis

Risk and scenario analysis is seen as essential in the literature [5, 6] this is however neglected during the design stage of an asset management system. The findings can be split into two sections.

Firstly, as the interviews were done during the financial crisis in 2013 financial implications on the market and market changes, as well as changes in customer requirements had not been factored into an asset management system design. This means that existing asset management designs should be challenged using scenarios considering as well changing market conditions. It became clear from the interviews, that higher risk on the assets in circulation, for example lowers investment servicing of assets or keeping assets longer in circulations, was not be taken into account. This however indeed can be critical to the company's survival when the market conditions (e.g. credit availability) would change.

Secondly, it was found that in many complex asset management systems the design was done using a specification, which then was used as a basis for a mathematical risk model. While mathematical models were seen as a great way for optimization of system, it does not allow a very high degree of flexibility as the type of models would only be working in the boundaries they were defined for. While these system designs are fully valid, a risk and scenario analysis was seen as a good way of testing the models and indeed of scoping the limitations of the system designed. It is then more a question of knowing what the system is good for and how the system is enabled to operate the best way and indeed understand the limitations. In addition, the people managing the system should then be enabled to manage in an efficient way. Hence if there is a need to make a decision to execute tasks against the systems recommendations, for example because of special events not being supported by the system, there needs to be processes in place to enable people to make decisions and to run the assets in an efficient way for that specific case.

3.2 Standardised Interfaces

It was seen that every organisation starts to build up a service ecosystem [8, 9] which contains various organisations involved in the management of their assets, most of which have their own AMS. There is therefore a need for a “standardised” interface for asset management systems to ensure value generation for the stakeholders. It is important for organisations thinking about a new design or a strategic redesign of their asset management system, to think about external interfaces.

There are often multiple stakeholders supplying parts to one asset management task within a system. Optimizing the communication between the partners within an ecosystem and bettering the value alignment between the partners will better the outcome of the service delivery ecosystem [8, 9]. There is the need to consider two aspects; one the managerial and two, the information technology systems side of communication.

On the managerial side it is seen as important that processes are implemented and discussed in the community which streamline the communication between partners of an ecosystem. At present there could be little or no literature and guidance found. Indeed there is scope for in-depth studies in these areas to define best practices.

On the IT systems side, communication between partners to align the delivery of services should be considered. If these systems are in existence however they are either build on ad hoc basis or are highly customised IT solutions. Hence there is the need for further investigation into the interfaces and exchange of information between two and more entities in an asset management system.

The authors are in agreement that there is a potential for standardisation for both the above and hence a reduction of costs to enable seamless communication between stakeholders through interfacing their IT Systems and bettering the communication processes.

3.3 Definition of Performance Measures and KPIs

There is a need to define KPIs/performance measures for the service asset management system in two focus areas. First the organisation has to see as much as possible the long term potential and take out the short term overall view when it comes to asset management. There were for example KPIs defined which had to do with cost cutting in some organisations, which have been found to hinder effective asset management in other organisations in the ecosystem. Decisions like cost cuts usually support a short term view, which may be very much needed at the time. However, maximisation of the value of the asset and an idealised focus on when to purchase a new asset at the right time is crucial in some situations. Hence making a purchasing decision on the basis of capital cost may seem to be driving down expenses in the short term, however in the longer term these may be driving the baseline costs high and lower customer satisfaction. Linked with the above area of risk management, these situations may focus on a long term planning for financially difficult times rather than a short term reduction of costs.

KPIs need to be aligned to ensure an effective asset management across an entire ecosystem. There have been multiple cases in interviews were for example site operators on building sites were not releasing machinery to other building sites within the company to ensure the availability of spare machinery in case of need. The argument for the behaviour was that the site manager was incentivised to keep his site running, but not incentivised to share his assets and resources with other sites when needed. The protectionist behaviour on one site had led to higher costs on other sites and hence to overall higher costs for the company as a whole. There is hence the need to incentivise the correct management of assets throughout the organisation and incentivise sharing where needed.

3.4 End-Value of Value Chain

End-value is the value that the user of the asset obtains from the use of the asset [10, 11]. For instance, an earth-moving equipment for a mining company may be maintained by a subcontractor under contract to the OEM, but the end-value from the equipment is delivered to the mining company. Throughout the interviews in only one case there was a high clarity and transparency of end-value through the value chain. There is the need to communicate the end value throughout the organisation. This is to ensure that multiple companies involved in a service delivery work together to focus on providing value to the customer. There is the need for a certain flexibility left within the power of the local managers on the ground on the partnering companies. This will be allowing collaboration on the basis of lower level management. This flexibility within processes will leave the ability to problem solve to deliver maximum value and outcome to the end customer. Indeed this should be flexibility to deliver within the KPIs and within budget so that there is no over delivery.

3.5 Alignment and Value Distribution of Performance Measures

There was no indication that KPIs throughout all organisations were end value focused [11]. It is well known that services operations should always focus on the end value generated [10]. The cases indicate that specifically personal performance KPIs as well as department and wider KPIs do not incentivise the end value generated. The interviews show for example one building site having a shortage of equipment because of equipment failure and another site was not prepared to optimize the use of their equipment for the greater good of the company's customer. Moreover the other building side was even encouraged to keep a high spare capacity on a may need to have basis because of the penalisation of the management staff if production would be reduced. If the company value perspective would be within the KPIs of the site managers and hence exchange of equipment would be incentivised the exchange of equipment would be easier between sites and risks between sites reduced.

3.6 Changing Customers and Needs

Finally an effective AMS should have change management capability to adapt to changing customers and requirements. The case studies have shown that usually there was not a provision for a redesign of an asset management system encountered on the basis of customer needs. Generally the asset management was on a project basis and would hence be started with the project start date. Hence there was the ability visible to see an asset over a project lifetime, however no company could see the asset for its own lifetime view. Specifically an asset lifetime view is getting important when thinking about multiple customers and the sharing of assets between different customers. The interviews conducted show that organisations are mostly not able to optimize assets over multiple customers even when they know that this would be possible and a viable option to reduce costs and increase asset use. The cases showed that customer needs would be flexible and alternate in e.g. intensity of use of equipment. Hence a large digger would be needed once a month, while a small digger would be needed the rest of the month. The large digger was used on site for the customer all the time, however the customer paid for the use of a smaller equipment.

4 Conclusions

The case studies showed that organisations often do not have a structured methodology to design an Asset Management System from scratch—they strive to improve an existing system. Risk and scenario analysis (akin to FMEA) is essential during the solution design stage for a resilient asset management system. A service ecosystem will contain various organisations each running their own asset management systems. There is a need for a “standardised interface” for asset management systems to ensure value generation for the different stakeholders. A standardised interface will help minimise complexity and help in sharing data and information between stakeholders. When designing a service solution, it is essential to define KPIs and performance measures for the asset management system in addition to service-level KPIs and there is a need to align KPIs with the value generated to the end customer. It is essential to improve transparency of end-value through the value chain in order to cultivate and improve integrated working practices. An effective asset management system should also have an efficient change management capability to adapt to changing customer requirements.

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Factors Influencing the Quality of Manually Acquired Asset Data

Katrine Mahlamäki and Jussi Rämänen

Abstract Sensors provide plenty of data about assets in use. However, efficient service operations require asset data that cannot be acquired through sensors. For example, maintenance actions must be manually reported. We have observed many challenges with the quality of this manually gathered data, such as missing or inaccurate data. We conducted two case studies to find out the factors influencing manual data gathering. We combined the results of these case studies with a literature review to create a framework of manual data gathering. The framework describes how the quality of manually collected asset data is affected by the organization and culture, the tools used, the tasks and competences, and, most importantly, the people and their motivation for collecting the data. This framework helps managers in organizing the data collection work by visualizing the aspects that need to be considered. Further work should test the framework in an industrial context.

1 Introduction

Many suppliers still fail to recognize the strategic nature of their asset data and they do not invest enough in smart technologies to collect data systematically [1]. Although remote monitoring can often be utilized in asset data collection to some extent, observations from our case companies clearly indicate that there is plenty of asset data that requires manual acquisition. For example, reasons for an engine outage (failure/stand-by/maintenance) have to be manually input to an information system. We have observed that the quality of manually collected asset data is often not sufficient for business analyses. Betz [2] made similar observations in a study of several hundred cases within SAP-PM and discovered that more than 80 % of the

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_23

documentation of the performed repair activities consisted of only one sentence: “Maintained and repaired.” Typical operational impacts of poor data quality include customer dissatisfaction, increased costs and lowered employee job satisfaction [3].

By collecting, analyzing, and interpreting strategic product usage and process data suppliers can design and sell value-added services that enable customers to attain improvements in productivity and cost efficiency [1]. Kortelainen et al. [4] describe how maintenance and failure data can be used at a wood yard in calculating availability performance measures, which are essential in increasing production line efficiency. On the basis of the observations we have made in our case companies, we state that asset data plays an essential role in a number of functions. Firstly, this data can serve as a key source for making correct and accurate preventive maintenance plans. Furthermore, sales personnel may utilize up-to-date asset data as they make decisions on where to sell modernization packages or new, substitutive equipment. Correct and timely information can also be invaluable in order to provide customers with the best possible service level. For instance, one of the companies involved in our research uses asset data to optimize the operation of equipment installed in their customers’ sites. This has resulted in improved performance and savings for the customer.

The goal of this study is to improve the quality of manually gathered data. Previous literature has recognized the need for manually collected asset data and analyzed the data collection work from the viewpoint of motivation [5, 6] or managerial pressure and IT tools [7]. We combine these studies with our findings to create a holistic view of the data collection work. In our approach, this is achieved by building a conceptual framework of manual asset data gathering and by relating it to the industry practice. In this exploratory study, our research question is: what factors influence manual data collection and thus contribute to the quality of the collected data? By answering this question, we make both theoretical and managerial contributions. In order to contribute to the literature on service provision, we take the service provider’s point of view. Our approach offers maintenance service operations a novel framework that assists managers in understanding the elements that affect manual data collection. This is important in the design of data collection processes. The input of manually collected data should be as easy and convenient as possible, and a natural and integral part of other work duties.

The paper is structured as follows. We analyze literature on different aspects affecting manual data collection, followed by our research design. The empirical findings are then presented, including the manual data collection framework. Thereafter, we discuss our findings in relation to the existing body of knowledge and present managerial implications and limitations of our research. In the last section, we draw conclusions of the study and present avenues for further research.

2 Manual Asset Data Collection and Data Quality

Jalil et al. [8] studied the effect of data quality in spare parts planning. They observed that the gains of using asset data deteriorated because of systematic data errors: all installed base items reported at the headquarters location or at the primary stock location due to incomplete or missing location data, and data communication error due to mismatch in communication with the vendor of the installed base items. Lin et al. [9] found knowing-why to be the most critical prerequisite for high data quality in the data production processes. They also found that data collectors need management feedback and support, as well as effective communication among stakeholders. In the following, we present previous literature from the viewpoints of motivation, tools and instructions, tasks and competences, and organization and culture.

2.1 Motivation

Data collectors need to have motivation for doing the data collection. There are two types of motivation: intrinsic and extrinsic motivation [10]. Intrinsic motivation is the need to be adequate and in control; doing something because it is interesting or enjoyable. Extrinsic motivation comes from pursuing an external outcome, such as a monetary reward.

Murphy [5] studied intrinsic motivation for manual data collection and found that the attitudes of the data collector, alongside the norms of the group and the control of the individual, lead to greater intrinsic motivation and greater effort.

Furthermore, Betz [2] found one of the reasons behind poor maintenance documentation to be motivation: "maintainers have no direct benefit from providing a detailed documentation." As the maintainers do not have easy access to the information they are providing, they do not see benefits for doing the reporting. Failure occurs because some people are required to do additional work, but those people are not the ones who perceive a direct benefit from the work they do [11].

Unsworth et al. [6] used goal hierarchy theory to understand the psychological factors that lay behind manual data collection. The goal hierarchy describes how abstract, long-term goals and more concrete, short-term goals form a hierarchy and motivation is stronger for those tasks that are linked to higher-order goals. Also, Unsworth et al. [6] believe that by using goal hierarchy it is possible to choose the most appropriate intervention for a particular group of data collectors.

Molina et al. [7] studied the effect of managerial pressure on manual data collection and concluded that the effect was dependent on the individual: pressure from the supervisors to collect high quality data increased the performance of those operators who had a submissive identity towards their supervisors. However, for intrinsically motivated operators the use of managerial pressure was demotivating and reduced their collection of high quality data.

2.2 Tools and Instructions

Data collectors need tools that support their work and clear instructions for data collection. Sandtorv et al. [12] discovered the difficulty in developing specifications for complex equipment that would be interpreted in the same way by each data collector.

Molina et al. [7] studied the effect of tools to data collection. They found that there was still some resistance to the new technology. The operators in their study felt that the system was restrictive and slow. They stated that the data system was corrupt and that corruption made the end user data inaccurate even if they were actually writing down accurate data to the system.

In [2], the database was not comfortably searchable and access to the database was only possible by leaving the place of the defective machine and walking back to the office. This could result in up to 500 m of walking. Furthermore, in the current IT support, the maintenance history of the machine is stored case by case and in a process-oriented system, whereas the maintenance work is object-oriented; it is about the physical machine.

A tool for maintenance data collection was developed in [4]. Their goal was to motivate all employees to record disturbances as well as failures. They noticed that the most demanding task is to implement the data collection system at the mill, because the benefits of the data collection are not evident before the database contains enough information. Therefore training and motivation were needed before the mill personnel really started to collect the data.

2.3 Tasks and Competences

The technicians who collect the data need adequate competences for completing the task. Furthermore, their experience and tacit knowledge affects the quality of manually collected data. Sandtorv et al. [12] found challenges in getting people with adequate competences to collect the data in a data collection project for the offshore industry. Lin et al. [9] report on tremendous difficulties in an asset management system implementation due to the insufficient knowledge and skills of the technicians who were supposed to train others in using the new system.

2.4 Culture

Organizational culture has an effect on data collection work. Management commitment to data quality is critical [9, 13]. Sandtorv et al. [12] found the quality and availability of data to vary significantly between companies. Tayi and Ballou [14] identified inadequate specification of appropriate data quality level and lack of weight put on data quality as problem areas. Furthermore, Tee et al. [13] name data quality awareness as an important factor in the pursuit of high-quality data. Lin et al. [9] mention organizational readiness as a reflection of organizational culture and an important factor in the implementation of an asset management information system.

National cultures affect the work conducted in the divisions of multinational companies. Hofstede et al. [15] measured and analyzed the values that distinguish country cultures and grouped them according to five dimensions: power distance, individualism versus collectivism, masculinity versus femininity, uncertainty avoidance, and long-term orientation. Oikarinen and Nieminen [16] used Hofstede's theory in preparing for international user studies.

3 Methodology

Our main research question is: what issues affect manual data collection and thus contribute to the quality of the collected data? We conducted two exploratory and descriptive case studies to answer this question and for reaching a detailed understanding of the phenomenon of interest in its natural context [17]. The research involved two globally operating Finnish equipment manufacturers that also provide maintenance and operation services to the sold equipment. One of the companies also services competitors' equipment in addition to its own equipment.

During our research, material has been collected through interviews, contextual inquiry and group discussions with representatives from the involved companies. Our primary research interests steering the material collection were current workflows and work environment of maintenance workers, as well as motivational factors in manual data gathering. In this study, we have concentrated on data gathering by own personnel. However, we have identified other possible data collector groups: customer's personnel, other equipment users, and other instances, such as auditors [18].

We interviewed 13 people in various maintenance related positions (a maintenance director, a service business director, four maintenance development managers, a process owner, maintenance system manager, spare part manager and four maintenance managers). In addition, we conducted four contextual inquiries [19] in a real working environment of maintenance technicians. In these sessions, we interviewed the technicians and also formed a picture of the current use of data collection and reporting tools as well as identified possible problems and challenges with them. In addition, we observed the surroundings and context in the working environment as our sessions took place on site.

We identified issues affecting the manual data collection work from the interviews and observations. After grouping these issues we formed a framework describing the manual data collection work.

The framework was presented to representatives of the case companies, and the company representatives were asked to validate our interpretation of the situation from a practical point of view. These company participants agreed with the overall structure of the framework. After constructing the framework, we re-analyzed literature from the perspective of manual data gathering in order to identify the existing knowledge and to compare our findings with it.

4 Results

The quality of manually gathered asset data is a current challenge at our case companies, and the companies do not have means to deal with the issue. As one maintenance manager put it:

> If things would get fixed by shouting we would have already solved the problem.

We have organized the results from our case studies according to the framework depicted in Fig. 1. In the following sections we present the results according to the categories in the framework: motivation, tools, tasks and competencies, and organization and culture.

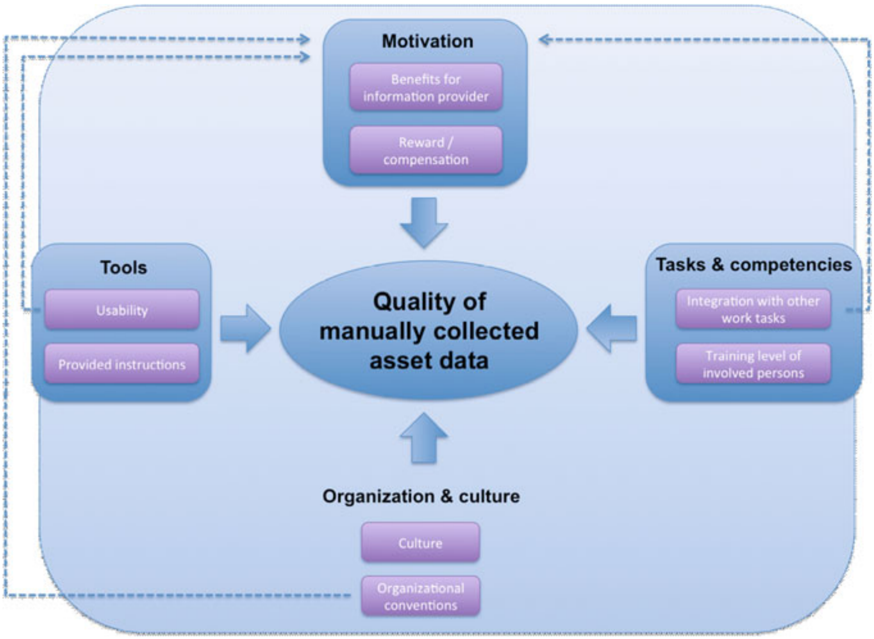

Fig. 1 Manual asset data gathering framework

4.1 Motivation

In our case companies, manual asset data collection is not part of the task descriptions. However, the maintenance technicians are expected to report all visits to customer sites and this back reporting is a part of the task descriptions. This information is used, for example, for billing the customer. The technicians are aware of this, and they understand that they must report their maintenance visit with a clear description of what they did at the customer site. Nevertheless, there is other information that they should report as well, such as reasons of failure, components that failed etc. This part of the reporting was not seen as important by the technicians. When asked about collecting other asset data as well during site visits, the technicians felt that there should be some kinds of incentive for them, either monetary or other kind of compensation:

> Reasonable compensation should be received. A warm thank you is nice but it doesn't keep you warm for long.

The technicians did, however, also see possibilities for intangible benefits for the information provider. One thing they mentioned was the understanding of what the information is used for. In addition, benefits to own work tasks, such as having a database of typical failures for each asset type was mentioned as a benefit that would provide incentive for data collection. Furthermore, benefits to others' tasks and making these benefits and the people benefiting visible to the information collector was also mentioned as desirable:

> At least it would be nice to get feedback if and how the provided information has been utilized and whether it has been useful.

4.2 Tools and Instructions

Usability of the tools is a prerequisite for collecting good quality data. If the solutions used in data collection have usability issues, people are less likely to be able and willing to provide the information.

> Giving leads to sales people is inconvenient because the tools are bad.
> The PDA is clumsy and freezes at times, its usability is not very good.

In addition to the tools, the instructions for data collection and reporting have to be clear. In one of our case companies there was no official data collecting methodology and no global instructions on how to enter information to the maintenance management system. This resulted in varied practices in different operating areas. For this company, also the customer reports some operational data. For this reporting, a certain level of reporting accuracy is agreed in the contract. However, there are no sanctions or rewarding policies in place to assure that the agreed level is met.

In the other company, some kind of training is given when going to site to introduce the tool used for reporting. However, people are creative and practices form and change, which may cause variation in the quality of collected data.

4.3 Tasks and Competencies

Insufficient training for data gathering affects data quality negatively. In addition, workers with varying competency levels may be involved in data gathering, which can result in data quality problems.

> Some people can express themselves in writing, others cannot.

In one company, part of the data collection was the maintenance manager's responsibility. However, the manager would sometimes ask the technicians to collect the data. Typically, this results in a less qualified person doing the data collection and usually this person is not aware of the agreed level of reporting quality.

The technicians generally felt that some extra reporting while on site would be ok:

> I could enter some additional information with the PDA with which the reporting is done anyways.

However, data collection should be integrated with other work tasks. If data collection causes deviation to current workflow there is less motivation for doing it. The technicians we interviewed were special repair technicians who had high control over their own work; they have freedom and responsibility for organizing their work. Therefore, data collection should not feel like a system for monitoring their work.

4.4 Culture

In one of our case companies the opinion at the headquarters was that the quality of manually collected data is best in India, whereas African and South American organizations have most room for improvement in their reporting practices. However, it was not clear to the managers what caused these differences in the data quality.

In one of our case companies we observed a very open culture, and the people we interviewed openly told their opinion about data collection practices. One maintenance manager was especially critical towards some of the practices:

> I don't see a reason for doing this reporting, so I've told my men that they don't need to do it. […] I would say the same thing if the CEO was sitting at this table. I have been telling this [the challenges with data collection] at [the country headquarters] again and again.

5 Discussion

5.1 Scientific Contribution

Previous literature has identified the different aspects affecting manual data collection, but not combined them in a single study. Molina et al. [7] discovered that that pressure from the supervisors was only important for those who had a submissive identity towards their supervisor. Combining this with our observation of the effect of culture on data collection, pressure from the supervisors could be seen most important in cultures that include submissive behaviour towards superiors. Kortelainen et al. [4] observed the need for training and motivation before mill personnel started collecting data with the tool they had developed. The same issues are elaborated in our framework, with the addition of cultural aspects, tasks, and competencies. Our holistic framework describes the human aspects in manual data collection work, thus synthesizing and complementing previous work.

We used Hofstede's et al. [15] cultural dimensions in an attempt to understand the differences in the quality of reported data from different countries. The scores that describe the country's relative stand on these cultural dimensions measured by Hofstede's et al. [15] are presented in Table 1 for India, Finland and Tanzania. The only dimension that follows the order of the perceived quality by the managers at the headquarters is long-term versus short-term orientation. This implies that a long-term orientation would motivate people for good quality reporting. Perhaps a long-term orientation enables the technicians to see the benefits of having a well-reported maintenance history of an asset, instead of only rushing to fix the machine and moving on to the next one.

5.2 Managerial Implications

We synthesized challenges found in our case studies into a conceptual framework. The manual asset data collection framework helps managers in identifying and balancing the different elements that have an effect on the quality of manually collected data. Figure 2 depicts the balance between the incentives and obstacles to manual data collection. Improvements can be achieved by analyzing the elements

Table 1 Hofstede's cultural dimension scores for India, Finland and Tanzania (Hofstede et al. [15])

Dimension	India	Finland	Tanzania
Power distance	77	33	70
Individualism versus collectivism	48	63	25
Masculinity versus femininity	56	26	40
Uncertainty avoidance	40	59	50
Long-term versus short-term orientation	60	41	30

Fig. 2 Balancing the incentives and obstacles to manual data collection

and by modifying the ones that are potentially reducing the quality of manually collected data. Such detailed understanding is especially valuable when a company is designing new data collection practices.

5.3 Limitations of Our Study

The primary limitation of our study comes from the exploratory nature of case studies. The chosen method enabled us to gather a detailed understanding of manual data collection in the case companies. However, the results are not directly generalizable to other contexts [17]. Our research was conducted in one country with two industrial companies. Although the companies have international operations, it would be beneficial to conduct additional studies in other countries to gain a better understanding of cultural aspects, for example.

We used multiple sources of evidence to increase the construct validity as proposed by Yin [17]. These sources included documentation, interviews and observations.

6 Conclusions

We have identified how the quality of manually gathered asset data is affected by the organization and culture, the tools used, the tasks and competencies, and most importantly, the motivation of the people collecting the data. There should be some kinds of benefits or rewards for the people collecting the data, either monetary or other kind. Data collectors need tools that support the data collection task, and they must have good instructions for the collection. Data collection should be integrated with other work tasks, and the persons involved should be given proper training for it. Finally, the organizational conventions should encourage data collection, and the influence of the surrounding culture should be taken into account. For example, if the culture is more collectivist than individualistic then rewarding the team for data collection might motivate more than individual rewards.

This study opens interesting opportunities for further research. More extensive empirical enquiry is needed to discover how culture affects manual data collection and the quality of collected data. This should include measuring the quality of reported data in various countries, comparing these results with Hofstede's cultural dimensions [15] and conducting interviews and observations in the respective countries to understand how culture affects the data collection work. Also, extent to which the experience and tacit knowledge of the data collectors affect the quality of manually collected data requires further studies. Another interesting avenue for future research would be in the design of data collection tools that would motivate data collectors to collect high quality data.

Acknowledgments This study has been funded by TEKES—the Finnish Funding Agency for Innovation and the case companies. The authors gratefully acknowledge this support.

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Potential for Local Government Entities to Use Mobile Devices to Record, Assess, Maintain, Utilize and Protect Their Municipal Infrastructure and Improve Their Disaster Management Capacity

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Abstract This paper discusses the findings from case studies of three organisations and their approach to the management of their fire hydrants. The purpose of the paper is to discuss the scope for better utilization and management of municipal infrastructure through the use of mobile devices for field data collection and the deployment of an intelligent incident management portal to benefit fire services and disaster management capacity. The study found that deploying mobile devices for field teams in conjunction with a web-based information management system would be considered useful. Although there is currently little technology in place especially web-based and mobile technology, there was an excitement and acceptance by the managers interviewed that such technology would improve current practice, especially with respect to information availability on critical facilities and the improved operational preparedness and capacity for disaster management. The key research contribution of this article includes an analysis of the data collection practise, information needs of first responders, development of a collaborative platform and process for supporting asset management and preparedness and emergency response. Also the demonstration of the data requirements and information sharing processes, in realistic disaster scenarios, and implementation and validation of the prototype system to demonstrate the concepts.

Keywords Facilities information sharing · Disaster management system · Asset data capture

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_24

1 Introduction

We are experiencing an increase in the total number of natural disasters worldwide averaging 400–500 a year, which is an increase from an average of 125 in the early 1980s [11]. There is a need for practical operational systems to deal with such disasters. Disaster Management does not only focus on the immediate response to a disaster, but also includes planning to identify risks, the preparedness to have a better understanding of the available capacity, the mitigation of risks and the relief and rehabilitation after an incident, as shown in Fig. 1.

However, recent research shows that as a society we are not sufficiently prepared for and capable of responding to large scale disasters in the best possible manner [3, 4, 11, 19]. Current disaster relief operations are subjected to various weaknesses that inhibit optimal decision making during disaster management operations. Obstacles in the disaster response process include "no communication, miscommunication and misleading information" [8] as well as the lack of access to information and the fact that there is no standardization, limited collaboration, coordination, and communication.

The 9/11 Commission Report [1] reported that during the emergency and the response operations, effective decision making was made very difficult due to constraints experienced in command and control and in internal communications to an degree that "incident commanders from responding agencies lacked knowledge of what other agencies and, in some cases, their own responders were doing" resulting in "command, control, and communication" challenges. The report recommended an improvement to "enable first responders to respond in a coordinated manner with the greatest possible awareness of the situation". Following analysis of Hurricane Katrina the Select Bipartisan Committee [16] specifically recommended that an information system be designed which allows users to record, monitor and share information more easily. As can be seen from the issues mentioned earlier,

Fig. 1 Disaster management life cycle

there is a definitive need for a process and platform which facilitates and fast tracks communication and information updates from the field during disaster occurrences.

First responders are at the forefront of response and recovery operations reporting on the extent of the damage, evacuation and relief requirements. Initial assessment of the affected buildings and households affected become the eyes and ears for the regulator and are critical to providing information that could enable critical and perhaps lifesaving decisions [14]. The planning and approach to a response effort can greatly be assisted by the availability of information relating to any critical infrastructure or facilities in the affected area. This information could range from critical facilities like chemical plants, to know what dangers are present; to where the closest working fire hydrant is; information about the stormwater network to more easily unblock the stormwater drains to reduce the impact of flooding; or the number and value of properties and infrastructure to assist with the quantification of damages.

Each agency responding to an incident scene has a different role and responsibility. They also add their own value to the scenario and can provide specialized information to assist in the management of the incident or disaster. This information sharing supports the incident and disaster response process. When the operators are in possession of additional information collected prior to the incident, and are able to access and seamlessly share such information, the operations and response teams would be even better informed and prepared. Such information could include fire hydrant location and status, building plans, critical facility assessment information and the planning for rehabilitation and recovery actions.

Fire Departments play a vital role in ensuring public safety. Fire fighters are required to respond quickly and effectively to fire incidents. This need for efficiency holds true for the important preventive activities Fire Departments complete such as routine inspections of fire hydrants. This helps ensure these systems will be operational when needed. The deployment of mobile fire inspection systems adds great benefit, and allows an organization to organize, conduct, document and report their inspections all from the field.

Information collected in the field relating to critical infrastructure can also benefit the asset management of the entity. It would add value to the asset register, condition and location of infrastructure. This information then contributes to the updating of the maintenance schedule of the assets and could even reduce the impact of any maintenance requirements throughout the maintenance and asset life cycle, as shown in the diagram below. The four elements are integral to the maintenance prevention (MP), preventative maintenance (PM) and corrective maintenance (CM) components of a comprehensive maintenance and reliability strategy, each of which, in turn, are important in the different life cycle phases of infrastructure asset management [2] (Fig. 2).

This chapter presents the case studies on three municipalities that have implemented an intelligent incident management portal for their operation and deployed mobile devices for their field teams to capture and share information from the field in near real time. This mobile web-based platform is deployed to improve the collaboration among the key actors involved in preparedness against (i.e. before

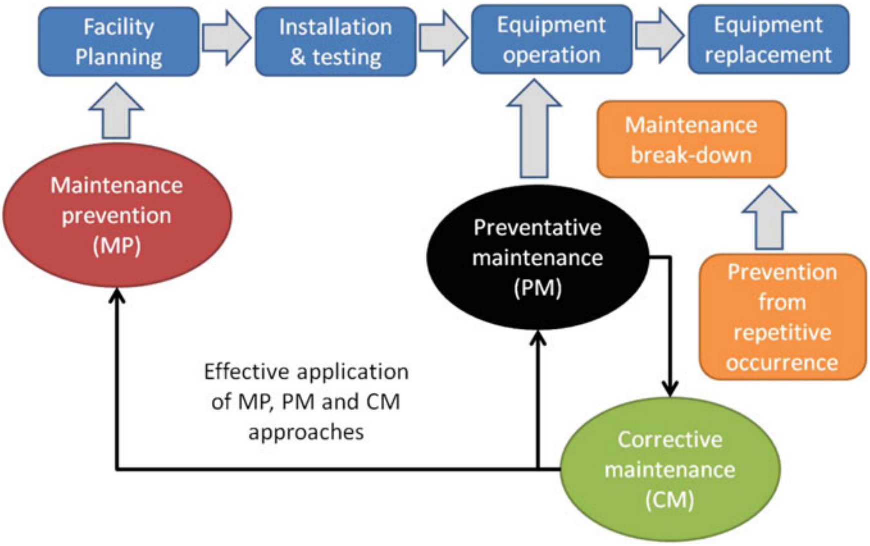

Fig. 2 Maintenance framework to extend the life span of assets

disaster), response to (i.e. during disaster) and recovery from (i.e. after disasters) major incidents or extreme events where multiple agencies including fire services and disaster management are involved.

This chapter has been structured as follows. Section 2 introduces related work and the impetus for this paper. Section 3 presents the methodology and approach while Sect. 4 discusses the key findings. Subsequently the contribution conveyed by the introduction of the intelligent incident management portal and the mobile field devices is discussed in Sect. 5. Finally, conclusions are discussed regarding the possible impact of the implementation of this system and possible research on future shared services incident management systems .

2 Literature Review

Lessons learned from previous major incidents highlight issues regarding lack of available information especially in spatial and electronic formats, as well as information flow, standardization, data coordination and integration, paper-based and error-prone forms, and information update issues between the field teams and the Joint Operations Centre, affected the response operation.

Use of different paper-based forms and systems at different levels of government (i.e. local, district, and province) lead to delays in providing a comprehensive damage assessment report and confusion because of incompatibility often results in reworking of the assessment reports. Occasionally, there is a need for reassessment as new information becomes available.

Paper-based data collection has been the main method for many years but there are many concerns regarding the data quality. Storage costs are exorbitant and the costs of rework and cleaning of data are extremely high. Electronic methods of data collection have been developed and improved in order to combine the process of data collection, data entry and quality checks in the field before data is submitted [17]. Handheld devices such as personal digital assistants (PDAs) are being used more and more as an improvement to the paper and pencil methods of data collection [15]. The use of PDAs is not without any difficulties, considering the challenges associated with having to download the data from the device as it is not viable to have laptops in the field. There are also additional risks associated with the use of PDAs, data can be corrupted if the device is damaged or data can be lost if PDAs are misplaced or stolen.

Wireless and mobile phone technologies have the potential to overcome some of these limitations. Low and middle-income countries present a lack of communication infrastructure to allow adequate fixed line internet access, while wireless networks allow access to telecommunications in areas where fixed lines are not present. In Africa, mobile users add up to 83 % of telephone subscribers, which is a far greater proportion than any other region in the world [22]. South Africa leads the African continent in mobile penetration with 36.4 mobile phones per 100 population [21]. Access to mobile phones is a normal occurrence even in remote areas of rural South Africa [18].

Studies have investigated the use of cell phones to transmit images for documentation [13] or diagnostic purposes [5, 12, 20]. However, few studies have investigated the use of mobile phones as a data collection tool, especially in low income countries. Finally, there are numerous anecdotal reports [9], but few published studies exist.

Disaster Management and other emergency services consist of many hands-on in the field operations. That is to say they are not performing work at their desks, but are out on location taking care of preparedness and emergency response tasks. Ideally, mobile workers need to interact with the intelligent incident management portal (IIMP) in the field, whether it is to contribute to the planning and preparedness information or response and situational updates or accessing reports and spatial information. They are typically not in the vicinity of a computer workstation. Organisations often rely on paper-based procedures to get information from the field, this information is mostly captured into a standalone excel spreadsheet and in limited cases this information is captured into a shared system. And even those agencies that have a system where multiple people can access the system, it is only from within their local network and not from the internet or outside their internal WAN.

Accessing information through easily accessible web browsers is now the norm both at home and in business, throughout the majority of South Africa. Reference [6] suggests that to improve efficiencies and the flow of data and processes, and to eliminate the amount of redundant data, in our case, more operational field staff like fire safety personnel and disaster management officers, need to be involved directly with business information.

The mobile and web-based technology available today offers the opportunity to incorporate fire safety personnel and disaster management officers, working in the field, to actively contribute to the organisation's knowledge base. Until now, such workers have had few opportunities to directly contribute to, or access, an entity's systems that hold vital information about its assets and infrastructure.

Also various emergency agencies are using Geographic Information Systems (GIS) in support of disaster management operations. The introduction of the latest technologies such as mobile GIS, high-resolution digital remote sensing imagery, global positioning systems, databases and digital video are also being evaluated for its benefit to emergency response operations [10].

This chapter discusses the scope for improving the utilisation and management of municipal infrastructure and service delivery during major incidents through the use of wireless web-based communications infrastructure, and the deployment of mobile devices for field teams, delivered via a web-based platform.

The following section of the paper outlines the methodology adopted and how this was implemented in the course of the study. The results are then presented for each of the case study organisations, broken down into the following key criteria:

- Organisation overview
- Current practise
- Identified key problems
- Technology
- Benefits of approach.

3 Method and Approach

The objective of the study was to investigate the current practise and existing technology, and the processes and benefits that are derived from the municipal infrastructure information gathered and how this can be linked with fire services and disaster management systems and processes. It is acknowledged that data collection, capture and dissemination in some form is extensively used regarding municipal infrastructure, but it is not immediately evident whether current methods are delivering the desired information, in a desired form, or in a timely enough manner for fire services and disaster management to derive the full benefit.

An appropriate approach for this type of research is to conduct case studies. To gain a sufficient amount of information for comparisons to be formulated, more than a single organisation needed to be considered. This study concerns the practices of three organisations varying in their location, level of fire and disaster management services and IT systems. The choice of these sectors was such that many different organisational facets could be covered, such as:

- Sphere of government (local, metro and district);
- Operational maturity of organisation (limited service to mature fire and disaster management service);
- Location of facilities; and
- IT systems in place (Paper-based, Excel and standalone documents to web-based systems).

The case studies approach presents a snapshot picture of each organisation at the current time and provides a brief assessment of where each is at in terms of managing their infrastructure data and the benefits they could derive from it. By considering three organisations from different spheres of government and level of operational maturity and IT systems in place, it is possible to identify similarities and differences between them and objectively determine if benefits can be achieved from their daily operations and the introduction of mobile and web-based technology.

The intention was to identify best practice and highlight weaknesses in current working practices, in order to establish the scope for improvement. The choice of the specific organisations selected was influenced by the availability of, and access to, key personnel. In all three cases, this included the heads of department for the respective organisations.

Prior to meeting key personnel, questionnaires were sent out to provide background on the research being undertaken, and to gather numerical data and similar information which might be difficult or impractical to gather during the interviews themselves. In all cases the key personnel from each organisation had prepared answers for these questions and these proved useful documents to work from and explore further during the interviews.

This method helped optimise the allocated interview time, allowing the interviewer and interviewee to explore the subject to a greater degree in a more organic way. Each interview lasted between 1 and 2 h, for the initial interview. Follow up discussion session were arranged to get clarity on some topics and get more in depth understanding on other aspects.

Case Study 1

Sphere of government (*local, metro and district*). Case Study 1 is a district municipality. Disaster Management and Water Services is a district function. While the fire service is provided by the local municipalities, the district also has fire staff.

Operational maturity of organisation (*limited service to mature fire and disaster management service*). The disaster management service and disaster management centre is well established and have processes in place to perform the day to day operations. There appears to be room for additional operational functions which can be performed by the district fire team.

Location offacilities. The main Disaster Management centre is located in the main town of the district. They have eight local municipalities which form the satellite stations of the district. The main fire station is in the main town of the district.

IT systems in place (*Paper-based, Excel and standalone documents to web-based systems*). A very comprehensive disaster management information system is in place in the District Disaster Management Centre and provides shared services functionality. The disaster management department uses the system on a day-to-day basis. The water and fire services have now started to utilize their various models but not to its full extent. The system includes mobile devices, web-based systems, graphs, reports, email and sms automated reporting and GIS.

Case Study 2

Sphere of government (*local, metro and district*). Case Study 2 is a Metro and provides water, fire and disaster management services.

Operational maturity of organisation (*limited service to mature fire and disaster management service*). Case Study 2 has a very large customer base and provides a very well established service to a demanding community. It is a large urban area which adds to the pressure of service delivery.

Location of facilities. The main office and fire station in located in the main town in the Metro. The Metro is divided into four zones. And the fire service consists of six fire stations.

IT systems in place (*Paper-based, Excel and standalone documents to web-based systems*). Many of the processes and systems in place use mainly paper-based methods with data capturing being done in Excel. The control room operates an outdated MS-DOS based system providing mainly Call Taking and Incident Logging functionality, with very limited reporting.

Case Study 3

Sphere of government (*local, metro and district*). Case Study 3 is a Local Municipality performing the main fire service for its district. It provides disaster management service on a local level but the coordination still remains the responsibility of the district. Water service remains a district function.

Operational maturity of organisation (*limited service to mature fire and disaster management service*). Disaster Management, Fire services and call centre operations are well established. The people and processes work well and provide one of the better services to a mainly urban and rapidly growing community.

Location of facilities. The main office and fire station are located in the main town of the local municipality, with a satellite fire station in town where the district main offices are located.

IT systems in place (*Paper-based, Excel and standalone documents to web-based systems*). Most of the processes and systems in place are use mainly paper-based methods with data capturing being done in Excel. The control room operates on hard copy occurrence books with daily shift reports compiled in excel. Mobile technology was recently introduced for the capturing of fire hydrant inspections, linked to a job card system for the maintenance of their fire hydrant system. This is integrated into a web-based information system which also has a web-based GIS module. Other modules are available through the system but not yet implemented.

Case Studies Comparison

Before starting with the comparison of the above case studies it is important to take note of the systems approach which combined people, processes and technology to provide a holistic solution. When all three of these factors are present and working together, is when the most benefits are achieved. From these case studies it

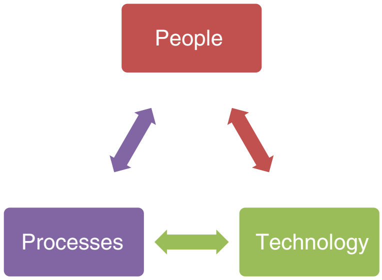

Fig. 3 Holistic model to consider when implementing systems

Table 1 Table providing a comparison summary of the case studies

	Case study 1	Case study 2	Case study 3
Sphere of government (local, metro and district)	District	Metro	Local
Operational maturity of organisation (limited service to mature fire and disaster management service)	Well established disaster management but room for operational improvement for fire services	Well established	Well established
IT systems in place (Paper-based, Excel and standalone documents to web-based systems)	Web-based intelligent incident management system with mobile technology and GIS, includes reporting	Mainly paper-based with excel and outdated MS DOS system in the call centre	Paper-based for most. Mobile technology for fire hydrant inspections linked to GIS web-based system
Limitations	Fire services with spare capacity to provide operational support	Lack of report, up to date systems and GIS. Limited accessibility to the system and no mobile devices	Mainly paper-based processes with excel data capture

is clear that not all components are present and implemented to the same extent which leaves clear areas for improvement (Fig. 3 and Table 1).

The discussion section compares and contrasts the organisations studied and their approach to capture and sharing of relevant information. Finally, conclusions are drawn and recommendations made together with an insight as to how this research can be taken forward in the future.

4 Findings and Recommendations

Table 2 summarises the findings from the case studies. From the discussions with relative municipal entities the *information that can be used* column is also added at the end of the table. This highlights the need for additional data to be collected in the field and be made readily available to the various role players.

Based on the excitement around the future of web services, Gilpin [7] predicts that most vendors should deploy web services technology mainly to extend the accessibly and functionality of existing platforms, applications and tools. Web services should not be seen as the building platform for completely new applications and environments. This provides the opportunity to challenge his prediction when considering this in the context of local government and entities like fire service and disaster management which have limited technology and systems in place, and aim to develop web-based systems rather than trying to integrate their current outdated and inadequate standalone systems.

Based on the findings from these case studies, it is recommended that these entities start concentrating on capturing information electronically rather than on paper, an example of a mobile application is shown below. This will increase the amount of information and the accessibility to access and share information. Information on a paper, PC or a standalone system is only worth something to a limited amount of users, and makes information sharing very difficult and time consuming (Fig. 4).

Information also adds more value if it can be spatially referenced and seen on a map, it provides an easy monitoring tool and can give some additional insight into the data. The figure below demonstrates a system which receives, interprets and reports on situation updates received from the field, updated via a mobile device (Fig. 5).

Table 2 Table of information currently being captured by the combination of all case studies

Life cycle Phase	Method of collecting	Content collected	Information that can be used
Planning	Mobile devices GIS Excel	Fire hydrant status and location. Critical facilities. Incident locations and damage assessments	Spatial location of existing infrastructure and demographics
Response	Paper-Based MS-DOS System Web-based system	Caller information. Incident information	Spatial location information on the infrastructure i.e. building and fire safety plans. Transportation and traffic conditions. Closest working fire hydrant. GIS for planning and allocation of resources. Resource and vehicle list
Relief	Mobile devices Excel	Critical infrastructure and housing damage assessment and relief requirement	Spatial location and extent of damage

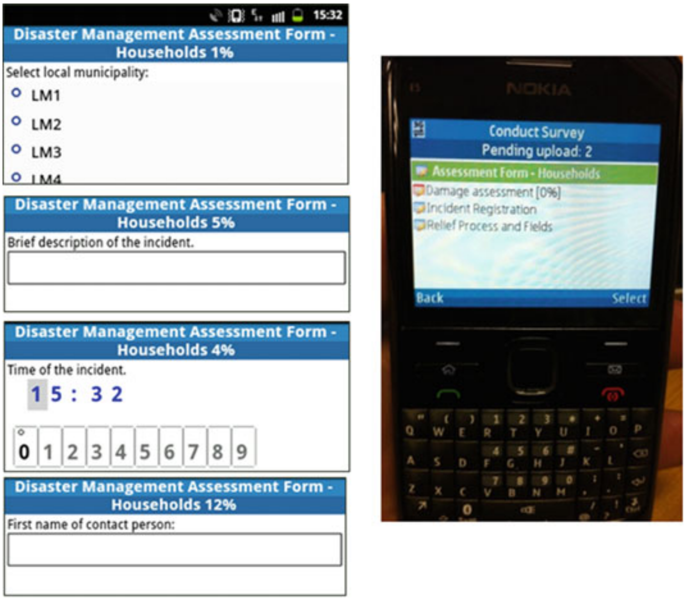

Fig. 4 Sample of the mobile device and application used to capture field data

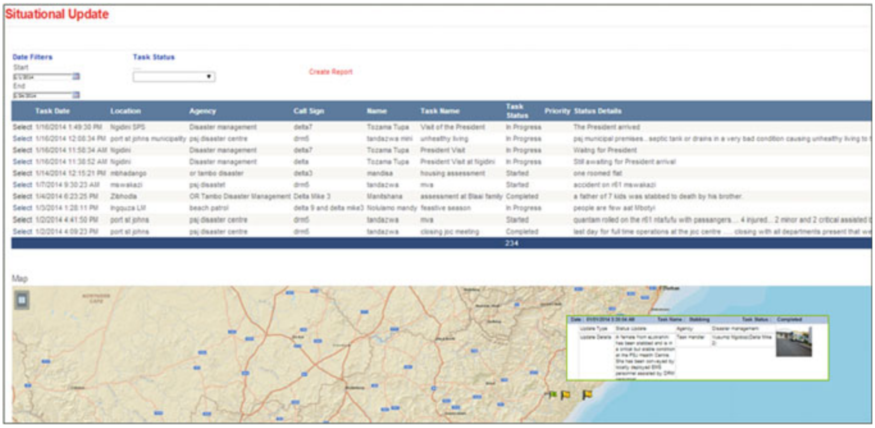

Fig. 5 Sample of situational updates received from the field using mobile devices

When data is captured electronically and integrated with other entities, which also introduces some standardization, it allows for faster reporting as well as automated reporting. This in turn can help to improve the process to assist affected communities and limit damage to infrastructure. Mobile devices introduced a new dynamic to data capture and are an ideal platform to allow for data capture and sharing of information, it is now much easier to collect data, as long as there is an information system which can receive and interpret the data being captured.

5 Contribution

The key research contribution of this article includes an analysis of the data collection practise, information needs of first responders, development of a collaborative platform and process for supporting asset management and preparedness and emergency response. Also the demonstration of the data requirements and information sharing processes, in realistic disaster scenarios, and implementation and validation of the prototype system to demonstrate the concepts.

The paper hopefully stimulates discussions and broadens the perspective of entities that could contribute to the mobile data collections and information sharing between entities and spheres of government, all of which can assist with the management of assets and the response to incidents and disasters.

Based on the outcome of the case studies reported here and other investigations, a web-based intelligent incident management system which incorporates the mobile technology approach to data collection and information sharing can add great benefits to various entities. Further work is focussing on the testing of the web-based and mobile platforms available, and the development of processes to achieve the benefits discussed in this article and to illustrate the key concepts.

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Cyber-Physical Systems in Future Maintenance

Jay Lee and Behrad Bagheri

Abstract Rapid and correct decision-making in big data environment is one of the most important challenges that companies are facing in today's business world. But regardless of this significant requirement, lack of smart analytical tools has made several aspects of industry not ready to handle big data. As more intelligence is integrated in industrial products and manufacturing lines, smart algorithms with self-aware, self-predict, and self-configure capabilities can further transform manufacturing equipment, fleet management and production systems to achieve resilient and autonomously optimized productivity and services. This article addresses the application of cyber-physical systems in the future of maintenance strategies.

Keywords Big data analytics · Intelligent maintenance · Cyber-physical systems

1 Introduction

In today's competitive world, intuitive fleet and production management plays significant role in survival and success of companies. To gain resilient service and product quality, company management requires transparent insight on assets, machine, products and personnel. In recent years, tremendous amount of research has been done to improve asset management strategies and companies are seeking to use most recent and intuitive technologies to facilitate their performance and gain safer, smarter and more sustainable environment. Through using these advanced technologies, factory transparency can be obtained to help managements have the

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_25

right information at the right time. This information consists of fleet or facility wide data that can be transformed into overall equipment efficiency (OEE) and other meaningful information to enable prediction and prevention capabilities. This worthwhile information helps to design the infrastructure of cost effective and just-in-time maintenance strategies.

Prognostics and health management (PHM) as the leading maintenance methodology to address invisible issues in industry, has been developed quite aggressively in recent years. Most invisible issues are due to component or system degradations, which result in unpredicted downtime and failures. In this regard, PHM methods are dedicated to trace assets condition by analysing sensory and system level data. In past few years, different aspects of industry as well as different machines or components have been targeted by researchers for developing the reliable PHM solutions. Aircraft engines [11], industrial robots [5], machine tools [8], electrical motors [3], wind turbine [6], batteries [1], gearboxes [4], bearings [10], pumps [9], railways [2] and etc. are only few examples of a broad range of assets that PHM methods have been applied on.

Among recent technologies, cyber-physical systems (CPS) is an ever-growing terminology representing the integration of computation and physical capabilities which has vast area of application in process control, medical devices, energy control, traffic control, aviation, advanced automated systems and smart structures [7]. In present time, CPS is in its immature stage and hence it covers a broad range of scientific area, significant amount of effort and research is required to develop and implement CPS based methodologies. In asset and fleet management applications, CPS provides self-awareness and self-maintenance intelligence. Predictive capability enables assets to proactively track their own status and predict potential failures and decide to issue relevant service requests. Additionally, CPS as the central hub for data and fleet management provides peer-to-peer health evaluation and component fusion based prediction methods where all of these applications are supposed to increase asset up time and relatively increase productivity and service quality.

2 Integrated Systems

In future maintenance, PHM methods can be applied as the analytical core of Cyber-Physical system. In current stage, PHM algorithms are applied to actual in situ data from assets but integration with CPS will help to leverage advantages from both parties. In the integrated case, historical life cycle information from entire fleet, peer-to-peer asset evaluation, which is available through CPS implementation, can significantly improve the performance of these analytical algorithms. As an example, in prognostics applications, high variety of failure modes requires rich historical information to help classifying the current status of the system with high reliability. Although acquiring every possible failure mode from one asset is very unlikely but by leveraging the features of an interconnected system, various failure modes happing among the fleet of similar assets can be captured and analyzed to be used as the generic failure signature of that particular asset. This capability is a huge achievement that is only possible by integrating CPS and PHM together in which a cyber model (avatar or twin model) of actual asset is created and operated on the cloud in parallel to real asset. Leveraging the integrated knowledge available in cyber physical model, health condition of assets can be accurately simulated and appropriately presented to dedicated users upon their demand without geographical limitations. Furthermore, the interconnectivity between fleet of identical assets to their cyber-physical model not only provides the opportunity of peer-to-peer evaluation and prognostic library accumulation but also enables PHM algorithms to have access to various life stages of different assets as well as test stage data.

3 Designing Cyber-Physical Based Maintenance Strategies

Knowing the capabilities of cyber-physical systems, a promising methodology for designing CPS based Maintenance applications can be developed. As it was discussed in previous section, interconnectivity provides access to vast amount of data. But, sole availability of data does not provide a significant advantage. Therefore, an adaptive and powerful methodology is required to manage, categorize and process data for further analysis by PHM algorithms. This method has to be broad enough to truly leverage all the advantages of cyber-physical systems.

In this paper we propose a systematic methodology for implementing CPS in maintenance applications which is called "Time Machine Methodology for Cyber-Physical Systems". This approach is in charge of perfectly organizing available data in Big Data environment to be prepared for usage in PHM algorithms in a way that every single asset from the fleet will have a cyber representative called Time Machine record. The task of this cyber twin is to extract and normalize information for further usage. Along with sensory data, implementation history, operation parameters, system configuration, maintenance events and etc. are other information that are extracted on the cyber side. The most important advantage of cyber model is its stability over time. Actual asset will fail after certain amount of time, but its cyber twin will keep its records for an unlimited duration. Unlimited existence of cyber twins results in continuous accumulation of Time Machine records and consequently gathering various operation parameters from broad range of identical components. Such information rich environment brings significant robustness to PHM algorithms for continuous and accurate predicting and monitoring of the factory. Finally, this methodology brings ultimate implementation of cyber physical system into action. Figure 1 shows the schematic view of CPS based maintenance strategies.

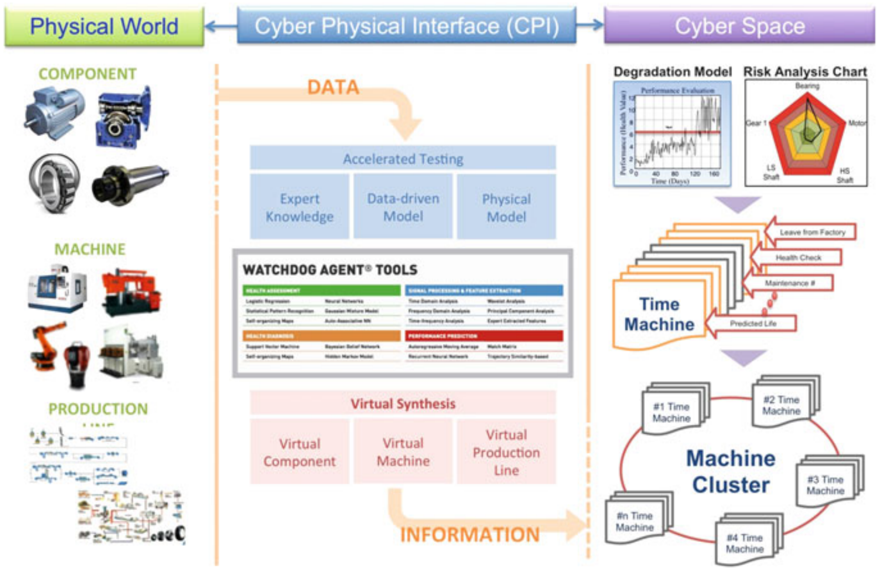

Fig. 1 Schematic view of cyber-physical based maintenance strategy

4 Industrial Case Studies

In this section we present two application of cyber-physical based maintenance on different fleet of assets. The first case study is health monitoring of off-shore wind-turbines, and the second case is development of a health monitoring solution for a fleet of industrial robots. The variety of applications shows the capability and applicability of CPS based maintenance solutions in various fields of industry.

4.1 CPS Based Wind Turbine Health Monitoring System

Efficiency and availability are the most critical metrics for wind turbine performance, and are influenced greatly by mechanical component degradation and failure. Optimal maintenance planning is a key factor in insuring both efficiency and availability of wind turbine assets.

A framework has been developed at the IMS Center for monitoring wind turbine performance at all three levels: fleet level, turbine level and component level. Both Supervisory Control And Data Acquisition (SCADA) data and Condition Monitoring System (CMS) data are utilized for obtaining the most accurate and complete performance information. At fleet level, a similarity-based method has been developed and patented, for clustering units into peer sets and determining individual performance based on comparison between peers within the same cluster. At turbine unit level, SCADA data is used to evaluate individual turbine power generation degradation, based on the deviation in power curve characteristics. Due to the dynamic environment and operating conditions for a wind turbine, a multi-regime method is employed to evaluate the degradation over time [6]. At component level, suitable signal processing tools are selected to analyse both SCADA and CMS data and diagnose various failure modes, such as planetary gear tooth scuffing, bearing outer race damage, shaft damage or imbalance and generator failures under multiple working regimes. Therefore, a reconfigurable wind turbine health monitoring system, depending on the type and amount of data available, is established.

The method for multi-regime power generation degradation assessment has been validated with an on-shore turbine, where degradation trends were observed that lead to major downtime periods, which could have been avoided if predictive maintenance was employed.

Various feature extraction methods have been developed for the method of predicting drive train component faults, to analyze vibration data under different operating regimes, and diagnose specific failure modes on a large-scale offshore turbine drive train (Fig. 2).

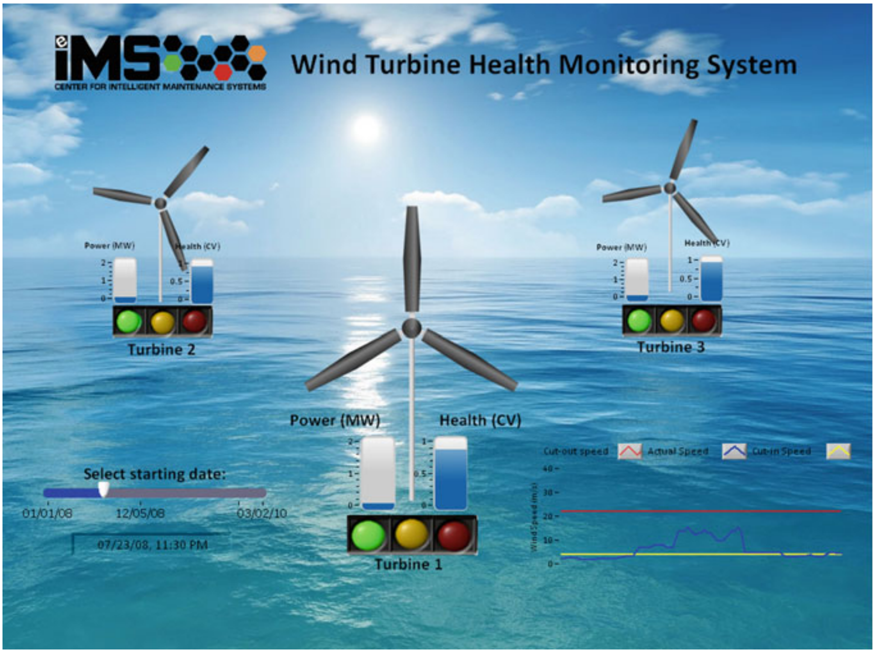

Fig. 2 Schematic view of wind turbine health monitoring system

4.2 CPS Based Industrial Robot Health Monitoring

This case study was focused on developing a predictive health monitoring solution for a fleet of 30 industrial robots in a manufacturing production line. Robots were handling various line speeds and therefore a complicated multi-regime cyber physical based maintenance approach has been conducted to tackle this problem. Figure 3 shows the schematic view of the cyber-physical model for current case study.

The multi-regime prognostics methodology was established using torque and speed parameters. Due to its non-invasive nature, torque monitoring is a popular fault detection method for monitoring health condition of industrial robots and therefore, most of the research efforts in this area have been focused on this parameter [5]. In addition, nonlinear relation between operating speed and torque cast a challenge on PHM algorithms to correctly determine the health state of the robot. In addition to condition data (torque and speed), the cyber physical model obtains various configuration parameters such as gear ratio, load ratio, pressure calibration, type of tooling for robot servo guns and assigned products to specific robots from production line. Configuration parameters provide computational core with more accurate understanding of the system and accurately clustering operation data for processing. At the final stage of implementation, the entire analytical engine of this study was established and set-up on the cloud server. The operation data from all assets in the fleet were stored on the cloud storage and health-monitoring algorithms leveraged the availability of the data to calculate the health

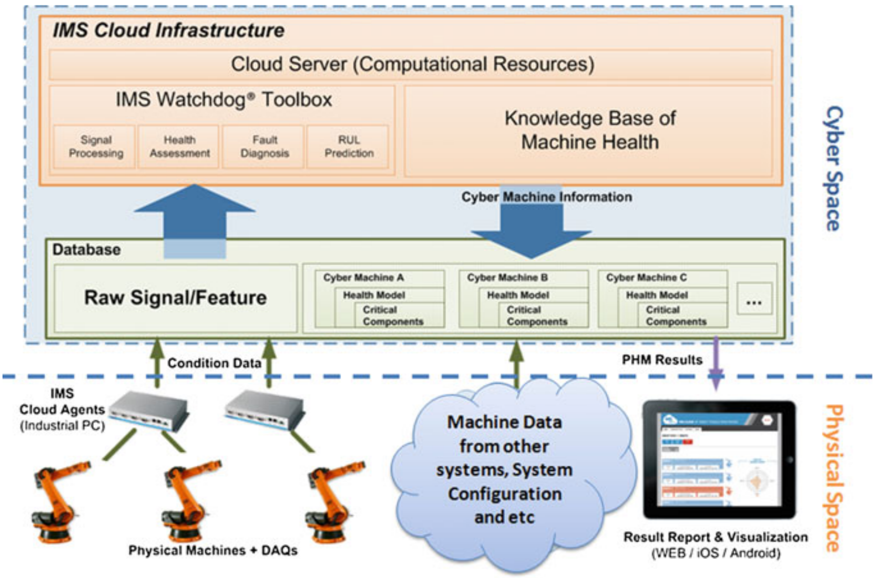

Fig. 3 Cyber-physical model for industrial robot monitoring

condition of each individual asset in the fleet. The outcome of PHM algorithms were transformed into graphical rich infographics and were presented to the end user through a web based user interface which was accessible from web-browsers.

5 Conclusion

In this paper we presented a futuristic view of maintenance by using Cyber-Physical systems that can improve fleet and asset management strategies into a completely new level by providing assets with self-maintenance and self-predicting capabilities. The methodology presented here is based on leveraging the interconnectivity offered by cyber-physical systems in Big Data environment for improving fleet and asset maintenance policies. Although at the time being, only few implementation of CPS based maintenance solutions have been established, such as two case studies presented in this article, but the increasing demand of industrial companies to leverage the next generation of asset maintenance methodologies can guarantee the effectiveness and popularity of this methodology in future.

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An Investigation into Technology Advancement for Switchgear at a Processing Plant

M.J. Sulaiman and J.K. Visser

Abstract Processing plants comprise a large diversity of mechanical, electrical and electronic systems and equipment. However, equipment eventually reaches the final stage of its useful life and further maintenance becomes unrealistic. The focus then shifts from maintenance to replacement. For electrical switchgear, the benefit of replacing obsolete equipment with technologically advanced equipment and not with similar equipment needs to be determined. Various authors have presented factors that impact negatively on technology advancement. However, none of these focus holistically on all the factors that might influence a final decision. A research project was done to develop and test a model that incorporates all the relevant factors that impact negatively on technology advancement. This model was used to determine whether the company would benefit from technology advancement through a survey. The results indicate that technology advancement for electrical switchgear was beneficial for the company.

Keywords Asset useful life · Technology obsolescence · Equipment replacement

1 Introduction

A South African processing company produces a variety of chemicals and a large facility was built in the 1970s. The operating equipment in various processing plants has now reached obsolescence. In 2003, the electrical engineering team responsible for power generation embarked on a site wide replacement strategy to ensure safety, stability, reliability, operability and sustainability of the processing plant. A phased replacement strategy was implemented and the replacement project was in phase nine in 2013 when this research project was performed.

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_26

The business case for the application for capital expenditure of the project focused on the safety of personnel, the probability of failure and the consequence of loss to the existing business, maintenance costs, unavailability of spares and the lack of data retrieval succeeding a failure. The tendency is to consider the most modern technology switchgear that is available. The rationale for this approach is that the latest technology would:

- Increase competitiveness by significantly mitigating the risk of downtime by improving the reliability and integrity of operations within the plant environment
- Substantially decrease safety and environmental risk
- Increase the speed of communication and information sharing by utilising latest information technology solutions
- Increase internal talent and experience in the ever-changing innovations front

Since 2003, new technology in the form of sulphur hexafluoride (SF_6) and vacuum circuit breakers, numeric/digital protection relays, arc detection systems and new PROFIBUS (a standard for communication in automation technology) systems have been installed in the plant with this aim in mind. The company did a large investment with regard to the phase 8 detail engineering and execution in the last 2 years. However, since the replacement strategy commenced, no audit was ever conducted to ascertain whether the facts and figures quantified in the business case have actually materialised. None of the assurances provided by manufacturers with regard to increased safety, increased reliability or reduced maintenance have ever been verified or confirmed in a practical environment similar to that of the company.

It is evident that the advancement in switchgear technology at the company has not been validated. The project team as a whole has not assessed the effectiveness of the new installed technology and whether such technology actually benefits the process plant in terms of safety, reliability, reduced maintenance, reduced downtime and competitiveness. Hence, the research was necessary to assist company management in terms of decision making with regard to future switchgear technology and to determine whether the decisions made in the previous installation were correct.

The main objective of this study was to determine whether technology advancement in switchgear was necessary for this specific processing plant and whether it would deliver on promised assurances in terms of (but not restricted to):

- Safety
- Risk mitigation with respect to failures (increased stability of the plant)
- Maintenance reduction
- Data retrieval

The goal of the research project was to develop a model that would facilitate in quantifying the benefit of technology advancement for a company. A further goal was to show that the proposed model that would be developed was valid and was useful for answering the research questions. It was therefore proposed that "advancement in switchgear technology would benefit the company".

2 Literature Survey

2.1 General

The company is constantly reassessing the state of its assets and is continuously striving to achieve a favourable level of asset management. Reference [4] mentions that the production competence of a company has large implications for the strategy, competitive strength and financial performance of the company. Hence, asset management is critical for a company to be competitive. However, at some point the equipment needs to be disposed of due to obsolescence. Bahrami et al. [2] point out that a preventive replacement strategy requires making decisions about when a piece of equipment should be replaced to reduce the occurrence of failures and minimize the downtime due to failure. The next phase of the strategy is to move forward with replacement when this stage is reached. At this point, one should identify which new technologies are necessary to ensure that (but not restricted to) uptime is maintained, safety is increased and maintenance is reduced.

A company must be forward looking to maintain competitiveness in the marketplace. Research has shown that, in the long term, the company that initiates and repeatedly introduces valuable technology advancements often obtains more benefits and outperforms the companies that follow and are less innovative [14, 20]. Numerous authors have alluded to the advantages of technology adoption.

- Gauvin and Sinha [9] mention productivity gains
- Patterson et al. [20] indicate improved inter-company communication and the capability to transfer more accurate and up-to-date information resulting in better visibility of demand and inventory
- Kans [11] mentions cost-effectiveness, cost reduction and improved access to data and information
- Badawy [1] illustrates profitability and growth
- Timmor and Rymon [23] allude to increased service quality, greater customer satisfaction, profitability and productivity
- Yam et al. [26] discuss operational and maintenance cost reduction as the result of a more accurate condition-based fault prediction

Porter [21] reveal that organizations adopt technological innovations to help them achieve competitive advantage. Various other authors [1, 5, 8, 13, 18] also mention competitive advantage as an essential benefit and growth for a company. Gagnon and Toulouse [8] allude to the fact that using technology nowadays is no longer a matter of choice but one of the essential features of most successful firms.

2.2 Factors that Impact Technology Advancement

i. *Stated benefits and implemented timelines*—The new technology must contribute a relative advantage to the equipment that it is replacing in order to make business sense. It is usually evaluated by examining the new innovation relative to whatever it replaced (Martino et al. [15]). Chau and Tam [5] support this statement saying that an adoption cannot be considered to be victorious unless the technology has been implemented as planned, within the allocated timeline and has assisted the business in achieving the promised results. Success must be measured by the effectiveness of the introduction of the new technology in achieving organizational goals [24].

ii. *Company size*—Patterson et al. [20] mention that the size of the organization can be a factor since larger organizations have the financial and technology resources to invest in new technologies and absorb any associated risks. They also have spare capacity to dedicate to adopting and implementing new technologies.

iii. *Company strategy*—It is often seen that the adoption of new technologies are not integrated into the company's corporate strategy. Managers frequently neglect technological factors in their strategic planning [8]. Nystrom et al. [19] observed that some top management teams have conservative attitudes toward innovation and prefer using current or time-tested methods. However, there are other top management teams that are risk-seeking, promoting the use of radical innovations to steer the business forward. These types of teams usually try to obtain a competitive edge for their company by regularly making drastic innovative changes and taking the intrinsic risks associated with the implementation of those innovations [19].

iv. *Company financial standing*—Miller and Chen [17] also found that a company's previous performance was negatively associated with the number of competitive practice changes. This can be explained via the fact that companies are likely to repeat actions that have been successful in the past (Cyert and March [7], Prahalad and Bettis [22]). The mindset is that if a solution worked in the past, it should work again. This is a major issue in terms of forward planning as this culture of decision-making can inhibit a company's flexibility to respond to environmental change (Clemons and Hann [6]). Consequently, if a company does not adapt to the changing environment, it will lose its competitive advantage in the marketplace.

v. *Integration*—Integration is defined as the ability of hardware or software systems to work with previously incompatible systems [25]. Karlsson et al. [12] mention the fact that the new technology must be able to accept new functionality in ways that minimize changes to the rest of the system.

vi. *Communication*—Karlsson et al. [12] state that there must be an appropriate fit between technology uncertainty and inter-organizational interaction. Hence, with high levels of technology uncertainty there is a need for greater inter-organizational interaction. All employees associated with or affected by the change should be involved in the process [18]. Liljander et al. [16] allude to the fact that communication is a necessary ingredient for technology adoption, but iterate that it can only be effective when combined with clear benefits for the customer.

vii. *Existing technology*—Karlsson et al. [12] state that prior company investments in previous generations of a technology might inhibit the adoption of later, more radical or complex alternatives. He cites examples of this, namely, if a firm must abandon existing know-how and acquire a new skill-base as a consequence of the introduction of a new technology, then they are likely to defend their outdated technology quite tenaciously. This is seconded by [20] who affirms that successful firms may have invested heavily in old technologies that have resulted in large costs and that these assets may have little usefulness if new technologies were adopted.

viii. *Employee insecurities*—Anderson and Tushman as quoted by [12] talk about competence-enhancing and competence-destroying technologies and mentions that the latter is inclined to stimulate defensive and resistant behaviour from those whose competences will be rendered obsolete. Lucas et al. [19] zero in on similar factors stating that younger employees are more likely to adopt technologies whereas older employees may have become so entrenched in past practices that they require a considerable amount of inertia to assimilate the new technology.

ix. *Training*—Boothby et al. [3] explain that simply investing in new technologies is not likely to provide a competitive advantage and that the full benefits of new technologies are only realized when training is included. Extensive investment is sometimes made in supporting hardware but not enough in training [13]. It is evident that knowledge depth, measured by the extent of professional training, affects innovation adoption (Chau and Tam [5]). Invariably, if a company integrates new technology successfully, it is indicative of the fact that their learning or employee competence is keeping up with the present state of technology.

x. *Alliance with suppliers*—With the advent of new technology integration, it becomes imperative that, in addition to the training of affected personnel, there must be a strong alliance between the company and the supplier of the technology. Many companies encountered difficulty with support and maintenance of both electronics and software [12]. Companies are now realizing that alliances are becoming an asset, increasing a company's technological information gap and thereby allowing personnel to be more aware of the technology's available options. As the level of technology sophistication increases, the need for external assistance becomes apparent.

3 Research Method

Many different authors, as mentioned in the previous section, researched the benefits of technology advancement and the reasons for its hindrance in organisations. It is evident from the literature review that the technical benefits are not the only aspects that should be considered when attempting to quantify the total benefits of technology advancement to an organisation. Various other concepts are also vital and should be incorporated. The aspects that were identified are:

- Stated benefits and implementation timeline
- Training
- Employee insecurities
- Alliances with suppliers
- Integration
- Communication
- Company strategy, existing technology, company financial standing
- Company size

These aspects mark the essence of the factors that impact on technology advancement. Therefore, it is understandable that if these items are not focussed upon and integrated into the implementation of the new technology, the advancement in technology will not benefit the organisation as a whole. All of these aspects need to be looked at collectively, not just as an aspect or concept by itself. Each author has focussed on either one or a few of the above mentioned aspects or factors to determine its effect on technology advancement. None of the authors present a model that encompasses all the identified elements.

A new model was proposed that comprises all the concepts mentioned above to correctly identify whether technology advancement benefits a company. This new model is shown in Fig. 1.

The research approach that was followed is summarized as:

- A thorough literature review
- Development of a model to provide a framework and direction for the research project
- Development of a survey questionnaire to produce the required research data for further analysis.

The survey design enabled a sample to be drawn from a population within the company. The sample population was all employees belonging to the electrical fraternity within the company. This included electrical artisans, electrical technicians, electrical group leader, section leaders, area leaders and the plant specific electrical engineers. Hence, all levels of the organisations were targeted. The questionnaire that was developed covered the eight categories proposed in the model in Fig. 1 using a 5 point Likert scale. It was envisioned that 121 questionnaires would be sent out to the respondents. This questionnaire was sent to personnel who were involved with switchgear via the company's e-mail system. The

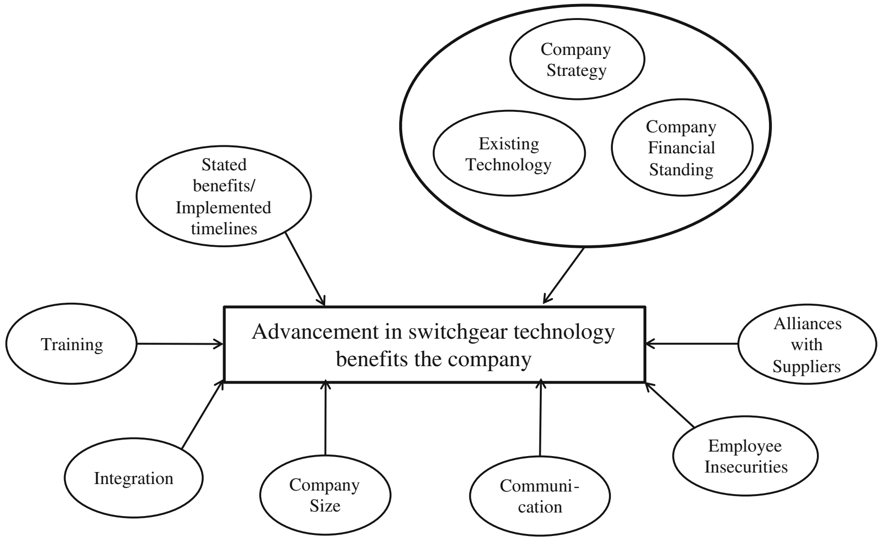

Fig. 1 New proposed model indicating factors or aspects that influence replacement decisions

questionnaire was coded in an Excel spreadsheet to enable easy completion by respondents.

An organization diagram depicting the employees from the different plants within the company is shown in Fig. 2. Only the Power Station subsystem has been expanded for explanation purposes. The major part of the analysis was centered on the validity of the proposition whether technology advancement in switchgear benefits the company. This was done by analysing the responses from the respondents in terms of the eight factors or categories that form part of the proposed model in Fig. 1.

An analysis was also done to determine whether a significant difference existed between the mindset of these engineers and technicians with regard to technology advancement. An independent sample T-test was conducted using the mean values and standard deviations of the eight categories of the two groups.

The “Engineers” group comprised the following positions in the company.

- Assistant engineers
- Engineers
- Senior engineers
- Principal engineers
- Area leaders

The “Technicians” group comprised the following positions in the company.

- Artisans and senior artisans
- Technicians and senior technicians
- Technologists and senior technologists

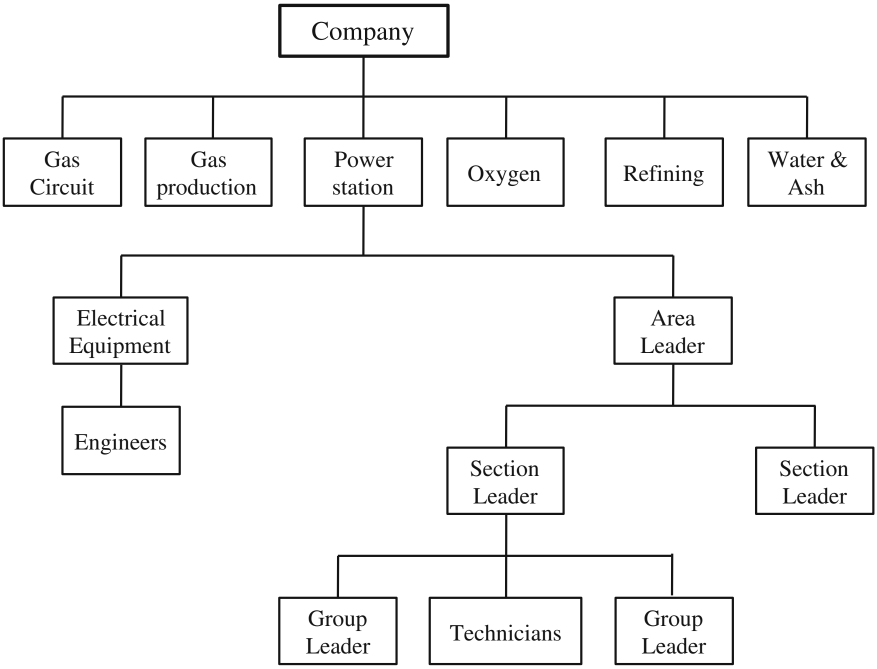

Fig. 2 Organization diagram of electrical fraternity

4 Research Data and Analysis

4.1 Research Data

A total of 121 questionnaires were sent out via e-mail to selected employees in the company and respondents were given 3 months to complete the questionnaire. Respondent were requested to indicate to what extent they agreed with 20 statements on a 5-point scale. Sixty respondents provided completed questionnaires that could be used for this study. Various questions were included in the questionnaire to test the validity of each of the eight categories. A reliability test was first conducted to allow the average to be used for the results of each category. The internal consistency coefficient, Cronbach's Alpha, was used to test the reliability. The SPSS statistical analysis software [10] was used to perform the test. These results are shown in Table 1. The "Integration" category was excluded since it comprised only one question and therefore the Cronbach's Alpha test was not required.

The Cronbach's Alpha values (greater than 0.7) show that the internal consistency is acceptable and that the average of the questions for each category could be used for the data analysis.

4.2 Data Analysis

The eight factors or categories used in the questionnaire were each given a percentage weighting as agreed with senior management as being indicative of the company environment. The 60 respondent's replies were analysed on the basis of the eight categories. The mean values, standard deviations and cumulative weighted averages are presented in Table 2.

The results in Table 1 indicate that the overall feedback from the respondents was positive. The mean values, presented in Table 2 for the eight categories, range from a minimum of 3.6 to a maximum of 4.5 (The mean value for the "employee insecurities" category counts the negative perception).

More than 78 % of the respondents agreed or strongly agreed with the 20 questions that were asked in the survey. The mean values for six categories were higher than 4.0 with only "training" and "alliances with suppliers" less than 4.0. This indicates that the overall perception of the respondents is that the switchgear team is implementing technology advancement in such a way that it benefits the company.

Table 1 Results of reliability test for grouped questions using the Cronbach's Alpha test

Categories for technology advancement	Grouped questions	Cronbach's Alpha
Stated benefits and timeline	Q1–Q4	0.742
Training	Q5–Q7	0.891
Employee insecurities	Q8–Q10	0.770
Alliances with suppliers	Q11–Q13	0.816
Communication	Q15–Q16	0.853
Company strategy, existing technology and financial standing	Q17–Q18	0.845
Company size	Q19–Q20	0.775

Table 2 Mean, standard deviation and weighted score for eight categories

No.	Categories for technology advancement	Mean	Std dev.	Weight (%)	Weighted score (%)
1	Stated benefits and timeline	4.2	0.62	20	16.8
2	Training	3.6	1.10	15	10.7
3	Employee insecurities	1.3	0.58	15	11.0
4	Alliances with suppliers	3.9	0.90	10	7.7
5	Integration	4.1	0.93	15	12.4
6	Communication	4.3	0.84	15	13.0
7	Company strategy, existing technology and financial standing	4.5	0.78	5	4.5
8	Company size	4.1	0.89	5	4.1
			Total	100	80.1

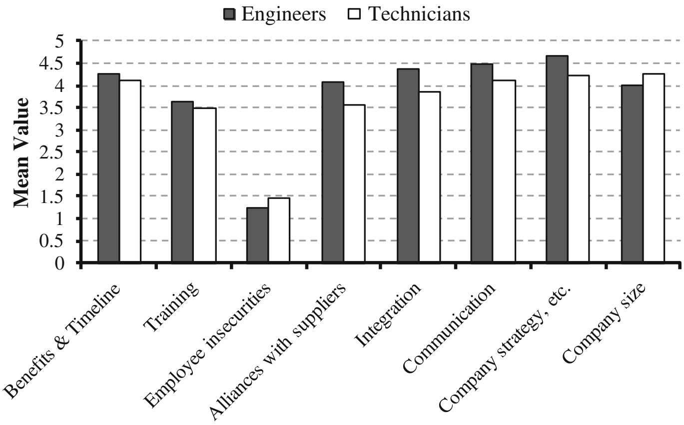

Fig. 3 Mean values for engineers and technicians for eight categories investigated

The category that represented the "stated benefits and timelines" did not have any negative replies from any of the 60 respondents. More than 90 % of the respondents in this category agreed or fully agreed with the stated benefits of increased safety, improved reliability and enhanced communication and that the project was completed within the allocated schedule. This indicated that the correct approach was pursued by the switchgear project team.

However, there were some instances that need further examination. Training is the only category in Table 2 that registers a significantly lower mean value and higher standard deviation than the other categories. It is indicative that this category is a contentious issue within the electrical fraternity and requires additional analysis. The high standard deviation alludes to the fact that many respondents may feel that the team does not administer the correct training or the right amount of training to ensure correct running of the plant. Nevertheless, it is evident that the team needs to focus more in this area to promote effective implementation of technology advancement.

The second portion of the analysis was split between engineers and technicians as explained in the previous section. The mean values for the eight categories are shown in the bar chart in Fig. 3 and the corresponding standard deviations are shown in Fig. 4.

Figure 3 indicates that the mean values for engineers and technicians are fairly close to each other. This signifies a similar mind-set amongst the two groups with regard to the eight categories of technology advancement. For six out of the eight categories the mean score for the engineers group was slightly higher than the mean score for the technicians. For two categories, i.e. "employee insecurities" and "company size" the mean score for the technicians were slightly higher. The biggest difference was for the "alliances with suppliers" and "integration" categories.

Figure 4 indicates that the standard deviation values for the technicians are larger when compared to the standard deviations for the engineers, except for the category

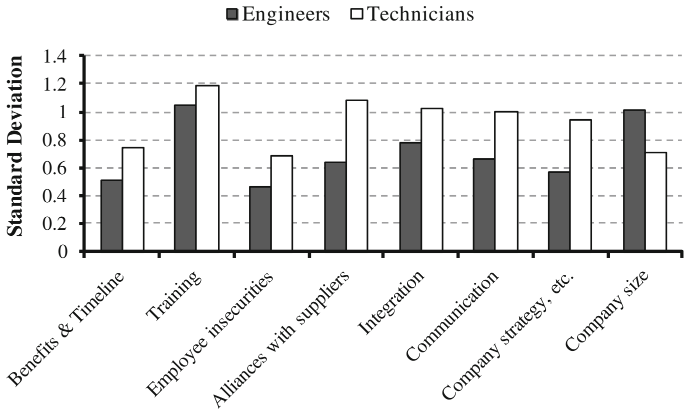

Fig. 4 Standard deviation values for engineers and technicians for eight categories

"company size". This indicates that there is more uncertainty amongst the technicians regarding the importance of the categories in terms of technology advancement. Although the results for the two groups were not significantly different, the following comment could be made regarding the two categories "alliances with supplies" and "integration".

With respect to the "alliances with suppliers" category, the result is indicative of the following:

- Despite the efforts/endeavours of the project team to ensure that the paperwork is in place for proper alliances with the relevant suppliers; the reality is that this does not filter down to the plant level which affects the artisans, technicians and technologists directly.
- Although a proper spare parts and interchangeability record (SPIR) list is developed at the end of each project, there is a "disconnect" between the stock holding department and the relevant supplier.

With respect to the "integration" category, the result is indicative of the fact that while the interface with the existing plant is developed prior to switchgear installation; there exists a sense of reluctance on the part of the "technician" colleagues. The integration of the new switchgear into the existing plant is well engineered and this difference in mind-set could be attributed to the existence of the new technology.

A standard t-test was done with the mean values and standard deviation values for the eight categories to test whether the results for the engineers were significantly different to the results for the technicians. It was found that the results did not differ significantly at a 95 % confidence level.

5 Concluding Remarks

The authors mentioned in Sect. 2 investigated the separate entities that contribute to the benefits of technology advancement. As part of a holistic approach to achieving the benefits of technology advancement, the proposed model presented in Fig. 2 was developed. This model has been analysed on the basis of the data received from the 60 respondents.

The mean values above 3.6 for all eight categories as derived from descriptive statistics illustrate that technology advancement in switchgear does benefit the company. The largest standard deviation was for the "training" category indicating that not all respondents were confident that training is adequate for new technology that is introduced. This category needs special attention from the project team in the next round of the switchgear replacement program to ensure overall success in the realm of technology advancement.

The descriptive statistics indicated a slight difference between the mind-set of the engineers and technicians with regard to "alliances with suppliers" and "integration". This indicates that these two categories are viewed differently by the two groups and the underlying factors for these differing views are presented in Sect. 4. Certain aspects of the standard deviation of the technicians group seemed clearly larger than others. As part of further research, it is recommended that the groups be further divided into plant specific areas. This would enable one to establish whether different plants or areas view technology advancement differently and might provide insight as to why some plants produce better results than others in the company environment.

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Failure Statistics: Budgeting Preventative Maintenance Activities Using Forecasted Work Orders

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Abstract Presently more and more organizations are replacing their reactive strategies for maintenance with proactive strategies such a preventative maintenance (PM). The goal being to maximize organizational profitability by decreasing asset downtime cost and increasing asset availability (therefore production). Successful implementation of PM activities necessitates a supporting budgeting strategy, set according to the maintenance need. PM needs can be quantified from asset failure frequency data using Failure Statistics (FS). Unfortunately, current budgeting strategies such as Traditional (Incremental) and Cost Replacement Value (CRV) budgets cannot integrate FS into its budgetary cycles. Recently, Work-Based Budgets (WBB) and Asset-Based Budgets (ABB) were put forward as alternative budgeting strategies. Their budgeting of proactive activities (PM) relies on attaining forecasted PM work orders. These work orders encompass all the PM activities planned for the budgeted year. Therefore, planning PM activities in line with FS, maintenance budgets (WBB and ABB) can finally incorporate PM needs into its budgetary cycles.

1 Introduction

Innovation suffers when good managers know something is not working, yet they continue with it. The introduction of something new, defined as innovation by Moore [20], has been lacking with regards to setting maintenance budgets. Too often management opts for simple, imprecise and non-evidence-based budgeting strategies such as Traditional (Incremental) or Cost Replacement Value (CRV)

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_27

budgeting. This can be attributed to the ignorance of management, as they only see maintenance as a bottomless pit of expenses or a necessary evil inferior to production [21].

Ironically, production is subject to maintenance, as effective maintenance ensures safe, reliable and available production equipment [26]. To facilitate effective maintenance, management must develop competencies in the form of maintenance functions [31].

One such function is the maintenance budget, which is a cost estimation of all the resources (materials, manpower, tools, overheads etc.) required to meet the anticipated maintenance workload for a specified period [12]. Along with the sales and production budgets, it plays a vital role in management's plans of achieving the production volumes necessary to meet the anticipated sales demands.

In turn, management's planning relies on correct foresight based on accurate forecasting [16]. Unfortunately, Traditional and CRV budgets are too elementary to incorporate the forecasting of asset failure frequencies into its budgetary cycles. Recently, two more intricate maintenance budgeting strategies were mooted as possible alternatives. Lamb [15] suggests Workload-Based Budgets (WBB), while Jonker [10] advocates the use of Asset-Based Budgets (ABB).

The setting of both these budgets rely on accurate forecasted work orders for its planned preventative maintenance (PM) activities. These activities can be scheduled appropriately once the frequency of asset failures are made quantifiable. A known tool or means for modelling past and predicting future asset failures, is Failure Statistics (FS).

For that reason, this paper probes the use of Failure Statistics (FS) in compiling forecasted PM work orders. These forecasted work orders can then be integrated into the setting of maintenance budgets (both WBB and ABB). The benefit for organizations would be the ability to accurately budget for PM activities according to PM needs, since both are determined using FS.

2 Maintenance and Maintenance Costs

Several definitions of maintenance exist, as useful as any is Márquez [18] who defines maintenance as:

> …the combination of all the technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function

The objective of maintenance is thus to serve the goal of any organization: increase profitability. Greater profitability is accomplished by decreasing expenses and increasing capacity. Expenses, such as downtime, are reduced by maximizing asset availability and ensuring the desired output quantity and quality are achieved in the most cost effective way possible [23].

2.1 Types of Maintenance

Asset managers have numerous methodologies such as Reliability Centered Maintenance (RCM), Total Production Maintenance (TPM) and Just-In-Time (JIT) Maintenance to consult when selecting a maintenance strategy. A few widely used maintenance strategies are presented in Fig. 1.

Design-out maintenance aims to redesign or eliminate the parts of an asset that requires excessive maintenance. Corrective (or reactive) maintenance awaits asset failure before maintenance is performed [1]. Contrarily, the purpose of preventative (or proactive) maintenance is to intervene prior to failure, thus preventing unexpected asset failure [22]. Preventative maintenance (PM) can be either Use Based Maintenance (UBM) or Predictive Maintenance (PdM).

UBM decisions are undertaken after a specified period of time or asset utilization, described in convenient parameters such as time, miles, tons etc. [26]. On the other hand, PdM assesses the asset condition (or state) and predicts its future condition by means of diagnostic measurements, for instance vibration monitoring, oil analysis, thermography etc. [17].

2.2 Cost of Maintenance

Life Cycle Costing (LCC) is an analysis technique used to determine all the costs related to an asset, from its inception to disposal [25]. Woodward [32] provides a more comprehensive definition:

> The life cycle cost of an item is the sum of all funds expended in support of the item from its conception and fabrication through its operation to the end of its useful life.

The four main life cycles of an asset and its accompanying costs are shown in Fig. 2. Operating cost accounts for a substantial portion of the life cycle cost of an asset. Within the operating cost are maintenance costs, which can deplete up to 40 % of the operating budget [9].

Manpower, materials and labour are typical examples of maintenance costs. Moreover, Woodward [32] states that maintenance costs can normally be broken up

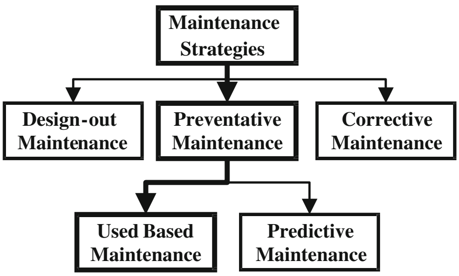


Fig. 1 Well-known maintenance strategies

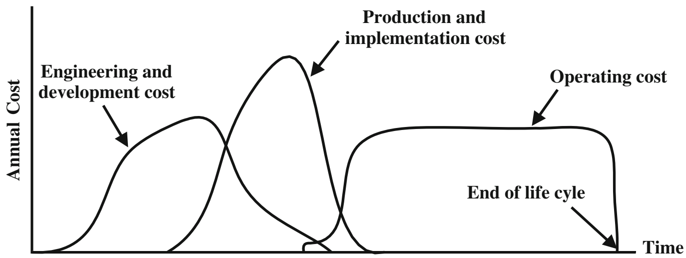


Fig. 2 Asset life cycles and its associated costs (Adapted from Woodward [32])

into the following classifications: planned maintenance, unplanned maintenance and sporadic maintenance.

Planned maintenance refers to Preventative Maintenance (PM), while unplanned maintenance denotes Corrective Maintenance (CM). Finally, major asset life refurbishment is an example of sporadic maintenance.

The implementation and amount of effort that each of these maintenance strategies (e.g. PM or CM) receive will have a direct impact on the maintenance cost and overall profitability of an organization [31]. Figure 3 shows how the implementation of PM and CM affects total maintenance cost.

An increase in PM effort reduces downtime cost, but uses more resources in the form of maintenance expenditure. Provided that appropriate time intervals are used, PM can reduce the frequency of unexpected failure as well as reducing cost [4]. In contrast thereto, an increase in CM effort actually decreases maintenance expenditure, but increases downtime cost. Downtime cost is generally more exorbitant than maintenance expenditure [31], since it takes significantly longer to correct a failure than it would to implement a scheduled maintenance activity [23]. Furthermore, organizations who only perform CM have shown to be inefficient as up to one-third of its maintenance expenditure can be attributed to waste (e.g. employee overtime) [31].

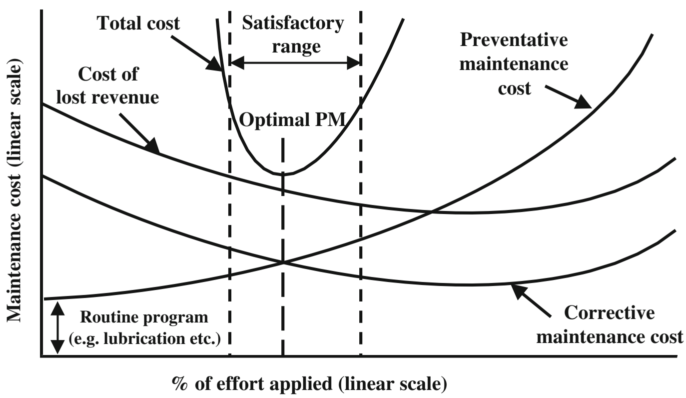


Fig. 3 Indication of how maintenance strategies can be optimized to reduce total maintenance cost (Adapted from Eti et al. [7])

The key is thus to determine the optimal amount of PM effort (Fig. 3) that ensures the least asset downtime at minimum total maintenance cost. To obtain and perform this optimal amount of PM, two requirements are necessary.

Firstly, a tool or means needs to be identified that is able to quantify the forecasted failure frequencies of assets. Thenceforth, the management will know precisely when asset failures are likely to occur and can therefore pre-emptively schedule and perform PM.

Secondly, a maintenance budgeting strategy that can integrate the use of this quantification tool needs to be selected. Having a supporting maintenance budget will ensure that the budgeted funds are accurate and therefore sufficient in helping to carry out the optimal amount of PM.

3 Maintenance Budgeting Strategies

Organizations can implement numerous budgeting strategies to support their maintenance activities. These strategies include established (current) strategies, which have been used for years, as well as recent (emerging) strategies that are gaining acceptance.

3.1 Current Strategies

Traditional (Incremental): Today, traditional budgets are arguably the most commonly used maintenance budgeting strategy in industry. Simply put, it is the previous year's maintenance budget with an additional allowance [30]. This allowance constitutes a certain percentage of the previous year's budget, but usually it only accounts for inflation [12].

In addition to its simplicity, consistency and ease of calculation, another advantage is its close linkage to the way other budgets (e.g. sales budget) are set. It is not devoid of criticism as its disadvantages include:

- Both its over- and under-budgeting hurts the organization's bottom-line [2].
- Generally underestimates maintenance needs, therefore maintenance practices are underfunded which escalates deferred maintenance [27].
- Poor form of budgeting as forecast does not attempt to deviate from what has gone before, hence innovation and cost reduction opportunities go begging [12].
- It is imprecise [3].
- Not evidence-based, resulting in maintenance budgets ending up being a negotiation between firm, plant and maintenance management [15].
- Allocated budget is not set according to maintenance need [19].
- Difficult to predict and rectify maintenance variances [10].

Table 1 Traditional maintenance budget (Adapted from Lamb [15])

Maintenance budget for 2014					
Account	2013	2014	January	February	March
Material issues	1,680,365	1,787,622	148,969	148,969	148,969
Contract services	1,109,409	1,180,222	98,352	98,352	98,352
Maintenance labour	3,796,516	4,038,847	336,571	336,571	336,571
Total	6,586,290	7,006,691	583,891	583,891	583,891

An example of a Traditional maintenance budget is shown in Table 1. The total budgeted maintenance amount for 2014 has increased by 6 % (inflation) from 2013. It is further divided *equally* to give monthly maintenance budgets.

Cost Replacement Value (CRV): These budgets are used less often than Traditional budgets owing to the greater complexity of calculation and the amount of research required. It is calculated by determining the total cost to replace all the assets (that require maintenance) at their present value and taking a certain percentage of that cost. This percentage varies, but generally ranges between two and four [27].

The main advantage is calculating the cost to replace assets at their present value. This information is a valuable planning tool when management ponders the procurement or auction of assets. Disadvantages are the same as those mentioned for Traditional budgets.

3.2 Emerging Strategies

Workload-Based: According to Lamb [15], Traditional maintenance budgets are fundamentally flawed in that they focus on maintenance resources as a basis for budgeting. This is apparent when examining the line entries of Table 1. The reality is that these resources merely serve as means to accomplishing the maintenance workload, thus *work* should be the foundation of maintenance budgets. This is the case for the line entries of the WBB in Table 2. The WBB consists of three sections: structure, workload and resource strategy.

The *structure* embodies all the maintenance activities planned for the budgeted year. These include the preventative, corrective as well as default project-driven (e.g. complete asset replacement) activities. Each activity is subdivided into work types (e.g. mechanical or electrical work) and assigned to its associated resources, which ensures accountability for both the work to be completed and its allocated resources.

Within each maintenance activity, the *workload* indicates the amount of work each work type will perform for the ensuing year. It is determined using business-to-workload models in the budget background, that are based on the organization's business plan.

Table 2 Example of an workload-based maintenance budget (Adapted from Lamb [15])

Maintenance budget for 2014							
Structure	Workload		Resource strategy				
Work type and class	Number of jobs		Labour		Material	Services	Total expense
	Month average	Year	Hours	Payroll			
Corrective							
Mechanical-MV	100	1,200	33,663	1,277,629	960,000	144,000	2,381,629
Piping-PF	43	516	14,475	549,380	412,800	61,920	1,024,100
Electrical	67	804	6,151	233,458	40,200	8,040	281,698
Instrumental	13	156	2,947	111,846	117,000	1,560	230,406
Subtotal	223	2,676	57,236	2,172,313	1,530,000	215,520	3,917,833
Proactive							
Preventive-MV	67	804	6,049	229,567	9,648	1,206	240,421
MAG	7	84	1,645	62,441	1,048	161	63,650
RBI	4	48	940	35,681	599	92	36,372
Electrical	12	144	2,938	111,502	1,872	288	113,662
Instrumental	75	900	4,250	161,316	35,100	2,700	199,116
Subtotal	165	1,980	15,822	600,507	48,267	4,447	653,221
Projects							
Mechanical-MV	N/A	10	13,247	502,769	80,000	434,500	1,017,269
Piping-PF	N/A	12	15,896	603,323	96,000	521,400	1,220,723
Electrical	N/A	0	0	0	0	0	0
Instrumental	N/A	2	1,889	71,696	29,000	0	100,696
Subtotal	N/A	24	31,032	1,177,788	205,000	955,900	2,338,688
Area total	388	4,680	104,090	3,950,608	1,783,267	1,175,867	6,909,742

Lastly, the *resource strategy* is a reflection of management's final decision with regards to the amount of resources that will be allocated to help meet the workload. These resources are subdivided into labour, material and services as well as being assigned to different work types within the different maintenance activities.

Asset-Based: In opposition to traditional maintenance budgeting, Jonker [10] proposes ABB as a means to control maintenance costs at an asset and not (or not only) a maintenance departmental level. His premises being that assets, and not the department, generate maintenance costs. This methodology differs in that the budget is built from the bottom up and is produced by following the six steps shown in Fig. 4.

The first step starts by scrutinizing the performance of the PM program of the previous year. Whether this program proved to be adequate in providing the required performance levels of asset utilization (uptime) is important and should be assessed before new decisions are made. This assessment is executed by performing a Reliability Centered Maintenance (RCM) analysis to evaluate where the current program needs adjustment. From here, individual maintenance activities for the

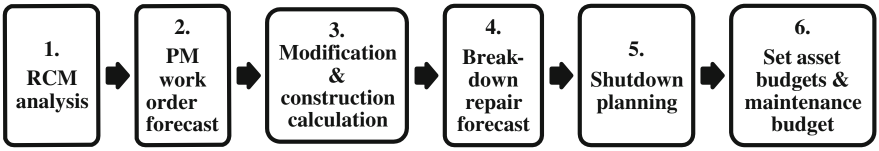


Fig. 4 Asset-based budgeting steps (Adapted from Jonker [10])

subsequent year are identified. These activities include preventative, corrective and default activities. All these activities are budgeted according to type in the following steps.

Step two involves the budgeting of the PM activities to be carried out on all the assets for the coming budgeted year. These activities are formalized in terms of *work order forecasts*. For greater clarity, work orders are further subdivided into cost types such as labour, materials or services.

The third step involves all the default project-driven activities, such as the expansion of an asset's functionality or its complete overhaul. These costs remain visibly separate in the budget as they do not form part of the costs associated with actually performing maintenance. Related projects are used as a basis for calculating these costs.

Step four involves corrective activities such breakdown repairs. These repairs cannot be scheduled at the beginning of the year, hence work orders cannot be used as a forecast. The budget for this step will be based on the expected cost of repair, which is calculated by the extrapolating of historical corrective cost data.

Some organizations have scheduled shutdowns and their frequency of shutdowns depend on the type of organization. Step five takes into account the costs associated with shutdowns. During shutdowns numerous preventative, corrective and default maintenance activities are executed in a short space of time. The costs of these activities are taken into account in the preceding steps and are entered visibly separate in the budget. This enables management to have greater control over the shutdown costs, which can deplete a significant portion of the maintenance budget.

Finally, the last step is to consolidate all the costs determined in step one to five into a concise asset budget (Table 3). The total maintenance budget is the sum of all the separate asset budgets.

4 Failure Statistics

Failure Statistics (FS) offer an avenue towards quantifying the forecasted failure frequencies of assets. It can therefore facilitate in ascertaining the optimal amount of PM effort illustrated in Fig. 3. PM can be either UBM or PdM as shown in Fig. 1. The latter is a more specialized and generally costly approach, often requiring skilled individuals [7]. Owing to its simplicity, smaller cost and ease of access to

Table 3 Example of an asset-based maintenance budget (Adapted from [10])

Maintenance budget for 2014						
Asset budget #1						
Asset budget #2						
Asset budget #3	Labour			Material	Services	Total expense
	Mechanical	Electrical	Instrumental			
Corrective (repairs)	1,040	2,080	500	1,560		5,180
Proactive (PM)	1,300	1,300		650		3,250
Projects						
Modifications and constructions	2,000		750	75,000		77,750
Shut downs		1,250			12,000	13,250
Area total	4,340	4,630	1,250	77,210	12,000	99,430

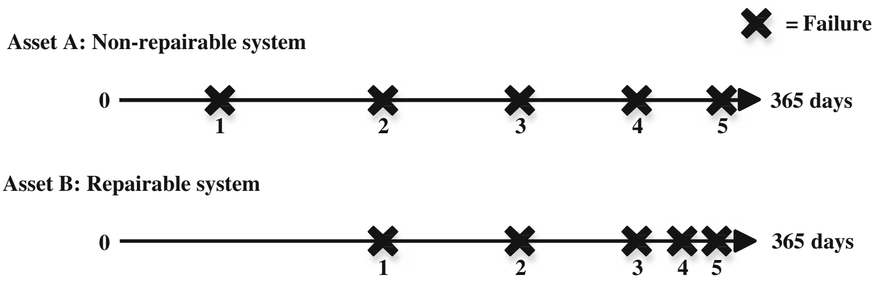


Fig. 5 Illustration of the danger of using MTBF

organizations, UBM is assumed to be the only technical and economically feasible maintenance strategy in this paper.

The need for FS is highlighted when examining the naivety of some maintenance practitioners and their misuse of Mean Time Between Failure (MTBF). MTBF is defined as the average time between failures and is calculated by dividing an asset's life cycle by the number of failures suffered during that time [5]. Sadly this does not always give a fair reflection of the average time between failures as indicated by Fig. 5.

Even though both assets have the exact same life cycle (365 days), number of failures (five each) and therefore MTBF of 73 days, their failure rates are dissimilar. Asset *A*'s failures happen sporadically whereas Asset *B*'s failures demonstrate a clear escalation in failure frequency.

Vlok [28] makes the troubling revelation that MTBF is a widely used benchmark for planning maintenance practices and setting budgets. Clearly, the use of MTBF, as described, cannot ensure accurate maintenance scheduling nor budgets.

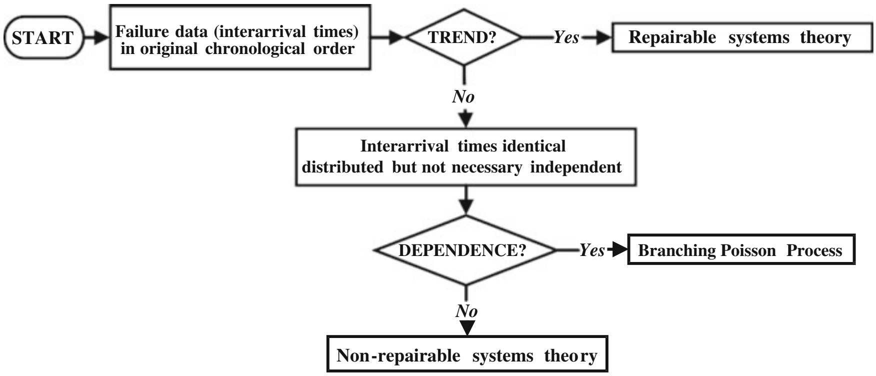


Fig. 6 Repairable and non-repairable system theory identification framework (Adapted from Vlok et al. [29])

This conundrum prompted research into inter-arrival times between failures which enabled researchers to classify Asset *A* and *B* as a non-repairable and repairable system respectively. A system is classified by consulting the identification framework presented in Fig. 6.

Classification starts by subjecting the data (inter-arrival times) to a trend test such as the Laplace trend test, recommended by KvalØy and Lindqvist [14]. Should a trend be present, the system is considered repairable. If the trend test reveals no trend, a second test for dependence follows. This test determines whether consecutive failures are dependent in the absence of a long term trend [6]. Should the data display a dependence, the Branch Poisson Process would be applicable, however Vlok [28] reveals that the dependence test is often omitted as it needs 30 observations to be performed with reasonable confidence. Therefore, in the absence of a trend, after the first test, a system is consider non-repairable.

4.1 Analyzing Non-repairable Systems

For data without an underlying failure trend, the Weibull distribution is widely used in reliability models due to its flexibility [11]. Vlok [28] expresses this distribution at instant x as:

$$f_x(x) = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta - 1} e^{\left(-\left(\frac{x}{\eta}\right)^{\beta}\right)} \tag{1}$$

where x, β and η denote continuous time, the Weibull distribution shape and scale parameters respectively. The distribution parameters are estimated numerically by maximizing the likelihood described by Vlok [28].

From Eq. 1, the probability of system failure $F_x(x)$ and survival $R_x(x)$ before a certain instant x can be derived. For the cases where $\beta = 1$, $\beta < 1$ and $\beta > 1$ the failure rate remains constant, increases and decreases respectively with time [11].

Residual or useful life of a non-repairable system, in operation for x units of time, can be calculated depending on its maintenance policy. If the policy conditions maintenance to be performed preventatively at time X_p or failure, whichever comes first, the remaining life till the next failure becomes:

$$\mu_{r+1} = \frac{\int_x^{X_p} x \cdot f_x(x)dx}{\int_x^{X_p} f_x(x)dx} - x \tag{2}$$

Otherwise, if the policy conditions maintenance to be performed only after failure, the residual life to the next failure is still calculated using Eq. 2, but with $X_p = \infty$, to account for the absence of any preventative action. *Note*: *the first term in* Eq. 2 *is the MTBF for a non-repairable system.*

In addition to residual life, the PM instant X_p (if obeyed) for a non-repairable system that will lead to long term cost optimization, can also be determined. The cost per unit time is calculated as follows:

$$C(X_p) = \frac{C_p \cdot R(X_p) + C_f \cdot F(X_p)}{(X_p + a) \cdot R(X_p) + \left(\frac{\int_x^{X_p} x \cdot f_x(x)dx}{\int_x^{X_p} f_x(x)dx}\right) \cdot F(X_p)} \tag{3}$$

where C_p and C_f are the total costs of a preventative replacement and an unexpected failure. Also, the time it takes for preventative replacement and failure replacement are denoted by a and b. The optimal value for X_p is determined by differentiating Eq. 3, with respect to X_p, and taking the minimum $C(X_p)$ value.

4.2 Analyzing Repairable Systems

For data with an underlying failure trend, the Non-Homogenous Poisson Process (NHPP) model has become favourable for modelling repairable systems [17]. Two formats (Log-linear and Power Law) of the NHPP have been generally accepted in literature [13]. For the sake of brevity, only the Log-linear format is discussed. For further information concerning the NHPP Power Law see Coetzee [6], who expresses the NHPP Log-linear as:

$$\rho_1(T) = e^{\alpha_0 + \alpha_1 T} \tag{4}$$

with $\alpha_0 > -\infty, 1 < \alpha_1 < \infty$ and $T \geq 0$. The parameters (α_0 and α_1) are estimated by using the Maximum Likelihood method described in Coetzee [6]. The MTBF for the interval from T_1 to T_2 is calculated as follows:

$$MTBF_1(T_1\ to\ T_2) = \frac{\propto_1 (T_2 - T_1)}{e^{\propto_0}\left(e^{\alpha_1 T_2} - e^{\alpha_1 T_1}\right)} \tag{5}$$

Residual life for a repairable system is computed using:

$$\mu_{r+1} = \frac{\ln[\propto_1 (r+1) + e^{\propto_0}] - \propto_0}{\propto_1} - T_r \tag{6}$$

where T_r is the last observed failure time and the final failure quantity is denoted using r. Long-term cost optimization for a repairable system can be expressed by the optimal global time (T^*) or optimal number of minimum repairs (N^*). The former, cost per unit time, is determined as follows:

$$C_R(T) = \frac{\left(\frac{1}{\propto_1} \cdot \left[e^{\alpha_0 + \alpha_1 T} - e^{\alpha_0}\right] - 1\right) \cdot C_m + C_s}{T} \tag{7}$$

where C_m and C_s denote the total cost on average to perform minimal repairs and total cost to replace entire system. The optimal global time (T^*) is the time (T) at which $C_R(T)$ is at its minimum. For more detail regarding the optimal number of minimum repairs, see Vlok [28].

5 Setting Preventative Maintenance Budgets from Forecasted Work Orders Using Failure Statistics

This section describes how organizations can use FS to compile forecasted work orders and subsequently preventative maintenance budgets.

5.1 Forecasted Work Orders Using Failure Statistics

Work orders are imperative to the documentation process of maintenance plans for the year [24]. A work order is created for a PM activity to be performed or an asset that has succumbed to failure [22]. Its objective is thus to provide ample information, to the relevant parties, regarding the planned PM activity or extent and nature of the broken down asset [8]. General consensus is that completed work orders should, at minimum, contain the following pertinent information:

- Unique identification number
- Description of work requested (PM or CM)
- Assigned priority
- Work location

- Expected and actual date of work commenced
- Description of expected and actual work performed
- Expected and actual duration of work performed
- Expected and actual resources (labour, material and service) used to complete work
- Expected and actual cost of work performed

Work orders for PM and CM are compiled prior to and after asset failure, respectively. For PM, its work orders are often referred to as forecasted work orders. FS can assist in compiling the pertinent information needed for forecasted work orders.

Firstly, using FS requires the failure data (inter-arrival times) of an asset (e.g. pump) or a component of that asset (e.g. impeller). Thus, the scope of the work order is predetermined when the failure data is collected. The work description and location are therefore known before FS is even consulted.

The importance of FS is realized in its ability to determine when PM should be performed. To begin with, it identifies the nature of failure data and classifies the asset (or its component) as either a repairable or non-repairable system. From here, the system can be represented by either the Weibull distribution (Eq. 1) or Log-linear NHPP (Eq. 4) model. Furthermore, the remaining useful life can be calculated using either Eqs. 2 or 6. This reveals when PM should be performed to avoid asset failure. However, this might not necessarily be the most cost effective time to perform PM. Fortunately in Eqs. 3 and 7, FS does have the ability to establish the PM instant that, if obeyed, will lead to the long term cost optimization.

Now that management has established the work scope as well as their optimal PM instant, they can start allocating resources appropriately. Resources include all the labour, materials (e.g. spares) and services needed to successfully perform PM. If management knows in advance which resources are needed, they can set out to procure them in the most cost effective and timely manner. Once suitable resources are acquired, their costs are formalized in the forecasted work orders.

5.2 Workload-Based Budgets from Forecasted Work Orders

Lamb [15] reveals that the workload in a WBB is calculated by using certain business-to-workload models. These models are not overly discussed, but the following remark is made:

> The concept of forming the workload profiles is obvious, but where does the data come from? The greatest single source is, of course, the EAM/CMMS. This is because it captures so many details for each work order.

A computerized maintenance management system (CMMS) provides, amongst others, an effective way to capture and manage an asset's failure history. Consequently, information can be extracted from the CMMS and put into work orders.

Forecasted work orders are established using FS (as described earlier). Therefore, the cost of resources for PM activities is consolidated into the *Proactive* structure of the WBB (Table 2). Each line entry now reveals the number of jobs it will partake in as well as its budgeted resources (labour, materials and services) for the year.

Other remaining parts of the WBB structure (corrective, dispatch and projects) cannot be budgeted with the aid of FS. The *Corrective* structure refers to the budgeted cost of maintenance activities that result from unexpected asset failure. FS cannot predict how much unexpected asset failure will occur in the next year.

Shutdowns or complete asset replacement costs are examples of *Project* structure entries. Only the PM activities within shutdowns and complete asset replacements can be budgeted for by using FS.

5.3 Asset-Based Budgets from Forecasted Work Orders

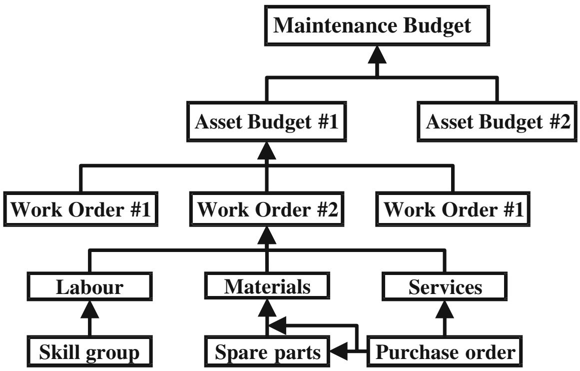
Step two of the Asset-Based budgeting process (Fig. 4) indicates that all the PM activities planned for the budgeted year are compiled in the form of work order forecasts. Again these forecasted work orders can be determined using FS.

Each work order forecast is assigned to the asset its work pertains to (as presented in Fig. 7). Each work order can be subdivided into the resources it will require. Resources include labour, material and services. These resources can be split up further for additional transparency.

An ABB is built from the bottom upwards. The cost of resources is merged into its appropriate work order. Next, a single asset budget (Table 3) is determined by adding the cost of all the assets' work orders. Finally, the total maintenance budget is established by tallying all the individual asset budgets.

Note that these work orders in Fig. 7 are the forecasted PM work orders. Only they can be determined using FS. Again FS cannot assist in budgeting for unexpected failures, therefore CM.

Fig. 7 Asset maintenance cost breakdown (Adapted from Jonker [10])



6 Limitations

There are certain limitations that adversely affect the setting of either WBB or ABB using FS. These limitations are centred on the collection of asset (or asset component) failure data (inter-arrival times).

Firstly, no failure data will be available for an asset purchased first-hand. FS cannot therefore be used to forecast PM activities, for the specific asset, for the ensuing financial year. In this case the asset should be maintained as stipulated by the manufacturer, supplier or warranty agreement. Where the foundation of the stipulated maintenance might be based on the statistical analysis of empirical tests conducted by the manufacturer.

Even with failure data available the data may be inaccurate, of poor quality, incomplete or even biased. This will naturally produce less accurate results. Thus, it is up to management to ensure data collection is as thorough as possible. Should it not be the case, management must deliberate whether to reject the results completely or use it as a baseline.

7 Conclusion

Literature highlighted the deficiencies of both Traditional and CRV maintenance budgets. Neither is able to incorporate the frequencies of asset failures into its budgetary cycles. As a consequence thereof, maintenance budgets are set oblivious to the asset's condition anticipated for the following budgeted year.

Two emerging maintenance budgets (WBB and ABB) were probed as possible alternative maintenance budgets. It was found to be possible with the aid of FS (an asset failure frequency quantification tool).

All FS requires is the failure data (inter-arrival times) of an asset (or asset component) to determine when PM should be performed. It can determine both the instant at which PM will avoid asset failure as well as when it will be most cost effective. Subsequently the PM need is established.

PM need is quenched by planning the resources necessary to perform it. The cost of these resources can then be consolidated into the forecasted work orders, where it will be spent. Once forecasted work orders are established, both WBB and ABB maintenance budgets can be set.

Unfortunately, FS can only be consulted with the availability of failure data. However, inaccuracies in the obtainment of failure data will ultimately be reflected in the results. Thus it is up to management to ensure the failure data subjected to FS are of satisfactory quality.

Another limitation is that FS can only assist the setting of proactive maintenance activities (PM) within maintenance budgets. Corrective maintenance (CM) activities (repairs) or project driven maintenance activities (shutdown and asset replacements) must be set separately when establishing the maintenance budget.

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Scheduled Shutdowns as an Incubator for Inefficiencies

E.J. Walker and P.J. Vlok

Abstract A scheduled shutdown is a period during which all or some of the production processes are stopped to allow for maintenance to be performed on machinery and equipment. Many organizations make use of scheduled shutdowns to reduce the risk of equipment failure during normal operating hours and to ensure that the machinery and equipment work at their maximum efficiency. Scheduled shutdowns are a huge cost to a company due to the lack of production during the shutdown period. Any activity that decreases productivity and availability of the process plant as a result of a scheduled shutdown is considered an inefficiency. This article investigates the inefficiencies incurred as a result of scheduled shutdowns. Inefficiencies of scheduled shutdowns explored include equipment unavailability, plant recovery time, resource allocation and the schedule of activities included in a planned shutdown. Scheduling of shutdowns was compared to the survival needs of people living on limited resources and those in situations of abundance. The concept of zero based budgeting practices was investigated for use to justify scheduled shutdowns.

1 Introduction

The International Organization for Standardization (ISO) has developed an international standard specifically pertaining to the management of assets—the ISO 55000 [1]. This standard defines strategies and common practices for the optimal management of an organization's physical assets. ISO 55000 considers the management of asset maintenance to be a functional policy within the whole asset management plan. This means that specific boundaries are determined by an

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_28

organization with respect to the maintenance strategy in order to control the maintenance of assets.

Scheduled shutdowns are a method of performing maintenance by the temporary shutdown of a production plant or factory so that equipment overhaul or replacement can take place [2]. This scheduled maintenance strategy has been utilized by manufacturing companies to perform maintenance on equipment and machinery for many years. The shutdown of a plant is very costly to a company as it is a period of no or limited production. It is because of this that maintenance periods are often perceived as areas of 'necessary evil' [3]. This article investigates the necessity involved in having scheduled shutdowns.

Scheduled shutdowns are important as they aim to retain equipment performance to ensure maximum plant efficiency [4]. This is vital to production plants as well maintained equipment leads to increased plant reliability and availability that in turn leads to increased productivity. Any activity that hinders plant reliability or availability or contributes to decreased productivity is considered as inefficient. Therefore focusing on identifying inefficiencies associated with scheduled maintenance procedures is important as these inefficiencies contribute to decreased plant productivity and profitability.

Much research has focused on the optimization and improvement of scheduled shutdowns specifically focusing on improving the processes within scheduled shutdowns such as the planning, scheduling of activities and resource management. This was covered extensively by [5, 6] who both propose policies and strategies for improving the planning and management of scheduled shutdowns. On the other hand, very little literature exists that focuses on the inefficiencies associated with and the justification of actually conducting a scheduled shutdown. The inefficiencies include suboptimal intervals between scheduled shutdowns [7] and maintenance work unnecessarily done during the shutdown [8].

This article investigates the inefficiencies experienced as a result of actually having a scheduled shutdown. Survival strategies utilized by communities living with scarce resources in the desert are applied to company thinking in terms of scheduling shutdowns. Zero based budgeting methodology is applied as a way to justify scheduling shutdowns and the frequency between them.

2 Inefficiencies Due to Scheduled Shutdowns

The shutdown of a plant or factory is an extremely expensive endeavour even though the shutdown period may be temporary. This is chiefly due to limited or no production during the shutdown period as well as the cost of actually performing the maintenance. These costs can be attributed to investments such as purchasing of necessary equipment and instruments as well as labour skill development [9]. In addition to these investments, purchasing and storing of spare parts and direct labour costs contribute to the cost of a scheduled shutdown [10].

Despite the huge cost associated with scheduling maintenance shutdowns, many companies still run shutdowns on a fixed-interval basis purely because this is how it has always been done [11]. This means that maintenance is scheduled for equipment based on a calendar date or how long the machine has been running as opposed to what condition the machine is in. Fixed-interval scheduling of shutdowns incurs large inefficiencies and often leads to avoidable costs and plant downtime. One reason for this is that fixed-interval maintenance policies also do not necessarily extend the life span of components as much as possible [12]. It has also been attested that maintenance performed too soon leads to losses due to the waste of residual life; on the other hand performing maintenance too late increases the risk of larger costs sustained due to unplanned failure [13]. Therefore instead of conducting shutdowns based on fixed-interval policies, they should be scheduled according to the condition of the equipment i.e. predictive maintenance.

Many activities included in the scheduled shutdowns are often unnecessarily performed during a plant shutdown. These activities are included in the schedule because no consideration has been made regarding the adjustment of the maintenance procedure so that in-line maintenance can be performed instead of having to do the maintenance during a shutdown. Therefore including only necessary and critical maintenance activities in the shutdown schedule reduces the inefficiencies of longer plant downtime and decreased productivity.

A case study concerning the company SABIC Innovative Plastics shows an example of the advantages of critical evaluation of the intervals between scheduled shutdowns as well as the activities included in the shutdowns. The study involved an investigation into the time needed between scheduled maintenance based on the condition of the machines. According to an analysis of the equipment condition, it was discovered that many maintenance activities included in the schedule of the annual shutdowns were unnecessary. Instead of annual scheduled shutdowns, most maintenance tasks were only required to be executed at intervals greater than 1 year. The activities were grouped together according to the condition that specific machines needed to be in before they required maintenance. After evaluating critical tasks and bottlenecks in the maintenance scheduled, the interval between scheduled shutdowns was extended from one to 4 years. This was considered to be a multi-million dollar financial saving by the company [14].

The case study of SABIC Innovative Plastics also exposed another inefficiency associated with the scheduling of shutdowns. This was that maintenance staff often sees the next scheduled shutdown as an opportunity to catch up on the “backlog of maintenance”. This is noncritical maintenance that has piled up during normal day to day operation of the plant. The inclusion of these maintenance tasks in the shutdown means that the schedule fills up with tasks that do not require complete shutdown. This then extends the duration of the shutdown that in turn increases the cost associated with plant downtime [14].

Industry consultations presented an unanticipated theory explaining the reason why scheduled shutdown periods are never reduced. Huge pressure is applied by management to the maintenance team to remain within the budget and deadline of scheduled shutdowns. The thinking is then that if the team completes all the scheduled maintenance tasks within half the time allocated for the scheduled shutdown then the allocated time for future shutdowns will be decreased thus increasing the pressure on the maintenance team. If the majority of the activities included in the shutdown schedule have been completed and there is time to spare before the end of the shutdown period, maintenance is often stretched out so that management does not identify an opportunity to reduce the period of future shutdowns. This strategy induces huge inefficiencies within the organization due to a lengthened period of avoidable non-productivity.

Another inefficiency identified as a result of having regular scheduled shutdowns (once per week or twice a month) during consultations with industry, is that maintenance normally performed in-line is delayed because of the knowledge that a scheduled shutdown will happen soon. The assumption is that the maintenance task will then be completed during the scheduled shutdown. This induces avoidable unavailability of the equipment due to its extended downtime between the time of failure and the scheduled shutdown. The culture in many processing plants generally involves the knowledge that inefficiencies should be reduced. However this thinking often does not extend as far as linking reduction in inefficiencies to the ultimate survival of the company.

Many companies need to be mindful of the fact that in many cases scheduled shutdowns are a luxury that can be ill afforded. In order to rectify the thinking of having to perform scheduled shutdowns, scheduled shutdowns can be seen as a scarce resource that must be carefully managed and used in order to minimise efficiencies and consequently survive.

3 Working Towards Survival

Despite the substantial costs involved with scheduled plant shutdowns the reason given by many companies as to why they have scheduled shutdowns in order to perform maintenance is because that is how they have always done it [11]. In today's highly competitive markets this excuse is no longer suitable as companies will not survive long if they continue to perform costly activities such as scheduled shutdowns that can be avoided.

Companies therefore need to be aware that they are no longer in a situation of abundant resources with the time and funds available to make mistakes and tolerate unnecessary expenses. Instead the need to consider the strategies involved with living and surviving with limited or scarce resources must be recognized. Such strategies are essential to the survival of people living in arid, desert regions where regular rainfall patterns and vegetation growth cannot be relied on.

The desert lifestyle is extreme and precarious due to the uncertainty of water and food sources. Despite this people have survived in deserts with limited resources for millennia [15] without the luxury of being able to go to the nearest convenience store to stock up on essentials such as food and water if they should run out. People have developed various strategies for the management and use of limited resources such as water and vegetation in order to survive in the desert. Traditional strategies aim to optimize the use and management of scarce resources to reduce the risk of shortages and thereby defer the fatal consequences of running out of these resources. In this way, the lives of traditional desert dwellers are adaptable as limited resources are conserved and only used as necessary [15]. Therefore it can be seen that survival with scarce resources is possible through good management practices and strategies.

In the context of a processing company, the limited resources of water and food in the desert are analogous to scheduled shutdowns. According to consultations with industry, the leading attitude currently associated to scheduled shutdowns is that they are necessary and therefore must happen at the specified time intervals. This approach is equivalent to a desert dweller being able to go to a local convenient store if they should run out of supplies and does not indicate a successful survival strategy.

Scheduled shutdowns should therefore be managed as a scarce or limited resource, without the luxury of being able to shut down the entire plant at given, unjustified intervals. This means that scheduled shutdowns will be employed as a method for maintenance only when absolutely necessary thus providing the company with a greater chance of survival as plant availability is maximised and costs reduced.

The strategies adopted by people living in deserts for limited resource use and management can be applied to production companies scheduling shutdowns. The key strategy that companies should adopt from traditional desert dwellers in terms of conducting scheduled shutdowns is adaptability to changing circumstances. People living in the desert do not stay in specific places for a set time every season that they pass through. Despite having well-known places that are frequented during the seasons no time frame is set to determine the length of stay in a particular area. Instead the people move when the necessity arises. This can be due to water and vegetation sources running low or severe sand storms in the area. Therefore the people adapt their movements to the current conditions of where they are staying. This 'density-dependent' strategy is also applied to the future destination of the group after it has been decided to move. The group must be able to adapt their future plans for destinations in order to account for current weather patterns such as sand storms, extreme temperatures and rainfall [15].

Adaptability is the capability to revise existing strategies and practices in the event of changing circumstances and conditions [16]. In terms of scheduled shutdowns these changes include the intervals between scheduled shutdowns as well as the activities included in the schedule of the shutdowns.

As discussed in Sect. 2, many activities included in shutdown schedules are unnecessary with inefficiencies induced due to the waste to residual life. Therefore the scheduling of shutdowns should be adaptable enough to accommodate for machines with different residual life spans. This might mean that during two scheduled shutdowns different activities will be performed in each of the shutdowns. In this way the time interval between scheduled shutdowns must also be adaptable to limit the waste of reduced residual life of equipment.

Another strategy that should be adopted from the traditional desert dwellers is that of the justification for moving to a new area in search of water and vegetation.

People who live in the desert remain in a place until the water source or vegetation growth is insufficient for survival. As soon as these resources become inadequate to support them or if another area seems more suitable due to unexpected rainfall, the people move to follow the rainfall or find other sources of water and vegetation. Full justification for the move and the destination must be provided because if a wrong decision is made in terms of leaving too soon, too late or going to the wrong place will mean that the people will perish [17].

Similarly to this, companies who cannot provide justification for performing scheduled shutdowns at specific times or those that make the wrong decision in terms of which activities to perform during a scheduled shutdowns induce inefficiencies. Companies operating with the attitude that scheduled shutdowns are a "necessary evil" [3] are bound to fail in today's increasingly competitive markets. This outdated attitude needs to be replaced for one that aims to profit from surviving with limited resources. Therefore companies need to become aware of exactly why scheduled shutdowns are conducted and aim to minimise the inefficiencies induced as a result of actually conducting scheduled shutdowns.

4 Zero-Based Methodology

Industry consultations indicated that the reasons why many companies have scheduled shutdowns are most often unknown. This means that most companies cannot explicitly justify why scheduled shutdowns are necessary or why they have them in the first place. Many companies are also unable to explain why certain time intervals between scheduled shutdowns are chosen. In the cases where a reason can be given, the main motivation is that a number of maintenance activities cannot be done while the plant is running. Despite this many companies cannot justify every individual task included in the shutdown schedule. In such cases it has been proven that less critical activities can more often than not be re-evaluated and often with slight, inexpensive adjustments the activities can be arranged such that they can be performed while the plant is still operational.

Other common justifications given by industry for the activities included in the schedule of a shutdown are legislation requirements or safety reasons. During consultation with industry, it was established that the intervals fixed for mandatory safety testing are often used for the justification of the interval of scheduled shutdowns. This induces inefficiencies associated with performing maintenance activities too early as discussed in Sect. 2.

A possible method to justify the necessity of scheduled shutdowns is to perform an analysis similar to that conducted for zero-based budgeting.

Zero-based budgeting is a method of preparing a budget for the next financial year as if it were a new budget essentially being prepared for the first time, instead of taking previous financial history into account. In this way every proposed expense within the budget is reviewed and its necessity justified. This method of preparing a budget aims to improve money spending efficiency and potentially reduce spending

[18]. Zero-based budgeting can be used as a way to assist in decision making [19]. The methodology generally utilized to prepare and evaluate budgets can be applied to planning and evaluating scheduled shutdowns for a process plant. Thus the decision making would focus on the frequency of scheduled shutdowns as well as the activities included in the schedule.

The advantages of the zero-based budgeting method include that it allows the budget to be flexible and adaptable to changing priorities and situations [20]. Applying the thinking involved in zero-based budgeting to the scheduling of plant shutdowns means that every shutdown and each individual activity within that shutdown will have to be justified. This idea essentially involves the thinking that at the start of a financial year the company starts off with the knowledge that no scheduled shutdowns will occur within the next year. Therefore, in order for a shutdown to be scheduled the maintenance manager(s) need to present a proposal detailing the reasons why a scheduled shutdown needs to take place. This proposal should include reasons why each of the activities will be included in the scheduled shutdown; these reasons should also be substantiated by failure statistics as deemed necessary.

The method also focuses on the value for money thus ensuring that each aspect included in the budget must be evaluated and [20]. If the maintenance manager is unable to present specific reasons why particular activities should be included in the shutdown schedule, or indeed why the shutdown should happen at all, then those activities will not be included in the scheduled shutdown. In this way, non-critical or unnecessary activities will be excluded from the shutdown schedule thus decreasing the time and cost of the shutdown.

Similarly to the advantages of zero-based budgeting, this method of justifying scheduled shutdowns allows the time between scheduled shutdowns to be flexible in terms of equipment getting older and less reliable [20]. This means that the time between scheduled shutdowns can be adapted as the time between failures decreases for aging equipment. Therefore the scheduled shutdowns will no longer be conducted at fixed time intervals but rather according to equipment condition as discussed in Sect. 2. This potentially reduces the number of scheduled shutdowns that will take place at an organization thus increasing productivity of the plant.

Few managers would deny that evaluating and justifying each aspect of the budget is valuable [21]. The same can be said for defending each of the activities included in the schedule of a shutdown in terms of focusing on its particular value for money [20]. This means that each activity included in the shutdown schedule is evaluated to determine whether performing maintenance will be a value adding task or not. If it is found that performing maintenance will add value by increasing reliability or availability of the equipment, then it is justified that the activity can be included in the shutdown schedule. In the case that it is found that limited or no value will be added by performing the maintenance activity, then it will not be included in the shutdown schedule.

The main disadvantage of the zero-based budgeting method is that it is very complex and therefore requires more time and resources to establish [21]. The disadvantage of implementing zero-based shutdown scheduling is also similar to that of zero-based budgeting in that the resources required to implement such a strategy will be substantially more than the traditional method of fixed-interval shutdown scheduling. This is because of the increased time that it takes to evaluate each activity within the shutdown schedule to determine if it should be included or not. Another disadvantage is that the scheduling of shutdowns will then rely greatly on the failure statistics of the equipment. Therefore in order for the zero-based scheduling method to be effective, the data associated with equipment failures needs to be detailed and comprehensive.

The advantages of implementing zero-based shutdown scheduling to reduce the number of scheduled shutdowns and thus increase plant productivity far outweigh the disadvantages. This method also ensures that each scheduled shutdown as well as each activity within those shutdowns will be completely justified. In this way it will be known that instead of scheduled shutdowns being periods of "necessary evil" [3] they will add value to the organization and ultimately lead to increased chances of survival.

5 Conclusion

Currently there is substantial research that focuses on the optimization of scheduled plant shutdowns. This includes the planning leading up to the shutdown, the execution of the shutdown and the review once the shutdown is complete. However, very little literature has been published with respect to the need for scheduled shutdowns and the justification behind actually conducting them. Therefore this article examined the inefficiencies associated with actually having a scheduled shutdown. Industry consultations established that scheduled shutdowns are the perfect breeding ground for inefficiencies, which have yet to be addressed. Companies should consider the concept of scheduled shutdowns and the associated inefficiencies as a whole instead of just those inefficiencies incurred during a scheduled shutdown.

A mind shift is required when considering scheduled shutdowns and we can take it on two schools of thought. The first is that of managing for company survival. Gone are the days when companies could afford having avoidable expenses. In today's highly competitive markets such waste and inefficiency will not sustain survival. Therefore strategies should be employed in which scheduled shutdowns are perceived as scarce resources that should only be conducted if necessary as opposed to using fixed-interval scheduling policies.

The second school of thought is that of the methodology of zero-based budgeting applied to the scheduling of shutdowns. This method ensures the justification of each scheduled shutdown as well as all the activities within the shutdown schedule. This minimises the inefficiencies associated with conducting scheduled shutdowns and aims to ensure maximum plant availability and productivity. Future research should aim to lessen the gap in literature regarding the scheduling of shutdowns with specific focus on the intervals between scheduled shutdowns.

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Part IV
Case Studies

Subsea Asset Maintenance on the NCS: On the Trends, Future Innovation, and Fitness of Life-of-Field

Agus Darmawan and Jayantha P. Liyanage

Abstract This paper studies the future subsea asset maintenance on the Norwegian Continental Shelf and evaluates the fitness of life-of-field. The future subsea asset maintenance is studied by analysing 15 subsea asset installation projects awarded on the Norwegian Continental Shelf in the last 10 years. The data were gathered from various reliable sources, including "FACTS 2013—The Norwegian Petroleum Sector" published by the Ministry of Petroleum and Energy and the Norwegian Petroleum Directorate. The sources also include websites of oil and gas companies and subsea contractors, and related publications. Life-of-field refers to services offered by subsea contractors to oil and gas companies once a field has started its production. This paper uses Subsea 7's installations as a case study. The fitness of life-of-field was assessed by comparison to future subsea asset maintenance on the Norwegian Continental Shelf. The success criteria and the fitness of life-of-field services can be used by oil and gas companies and subsea contractors to better enable subsea asset maintenance to perform its role effectively in oil and gas field development.

Keywords Asset maintenance · Oil and gas assets · Asset life

1 Introduction

Oil and gas (O&G) field development and operations involve a complex process. This in principal consists of five phases: Exploration, Appraisal, Development, Production, and Decommissioning. Subsea contractors such as Subsea 7 and Technip traditionally provide services to O&G companies during the Development

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_29

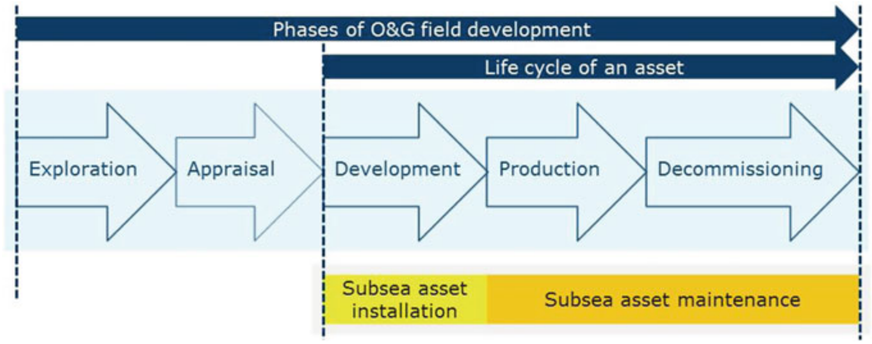


Fig. 1 Traditional paradigm of subsea asset installation and subsea asset maintenance

phase by performing design, fabrication and installation of offshore production systems. A production system consists of various upstream, midstream, and downstream functions. While midstream functions occur within the top-side production facilities, the upstream functions involve subsea, drilling, well and reservoir management processes. Within upstream activities, the subsea asset maintenance is mainly performed during the Production phase to maintain the subsea assets that subsea contractors have installed during the Development phase. It is a critical function because the subsea assets that need to be maintained often consist of complex equipment designed to perform critical functions and overcome extreme conditions [7]. For any particular asset, subsea asset maintenance has to be performed until the asset is decommissioned (Fig. 1).

According to the European Standards in maintenance [2], maintenance is defined as a combination of technical, administrative and managerial actions done during the life cycle of an asset with the objective of retaining the asset in, or to restore it to, a state where it can perform the required function. Thus, in order to effectively do its role in O&G field development, subsea asset maintenance needs to have maintenance processes which occur continuously during the life cycle of an asset. It is aligned with the idea of asset integrity management which, as mentioned in [4], emphasizes that the improvement of process capability should be applied in all steps during the life cycle of an asset. This approach will extend the lifetime and maintain the effectiveness of the asset [12].

In addition to continuous maintenance processes, subsea asset maintenance also relies on technology. Reference [5] describes how information technology (IT) systemizes and couples the processes in relation to the operation and maintenance of O&G production systems. Additionally, since its object is offshore production system, subsea asset maintenance also needs technical capabilities to enable its offshore operations. The technical capabilities include technical specification of specialized equipment and vessels from which the equipment are deployed, and the expertise of onshore and offshore crew.

In this context, the concept of life-of-field (LoF) was introduced for subsea assets on the Norwegian Continental Shelf (NCS) aiming at providing a comprehensive approach to improve subsea asset maintenance practice. As the conditions on the NCS have become quite challenging over the last few years, this has forced a trend to become relatively more innovation driven in the future. Subsea asset maintenance processes also demand new perspectives and solutions. This paper studies the developments on the Norwegian Continental Shelf, and the fitness of LoF concept with respect to forthcoming sectoral demands, and elaborates on the innovation-driven improvement actions.

2 Status Review: Future Subsea Asset Maintenance on the NCS

The future subsea asset maintenance on the NCS is identified by analyzing subsea asset installation projects awarded on the NCS in the last 10 years. This approach enables continuous maintenance process since the initiatives and challenges in the installation phase become recognizable for the maintenance phase.

2.1 Subsea Asset Installation Projects on the NCS

Table 1 shows 15 subsea asset installation projects [6] awarded on the NCS in the last 10 years. The projects are chosen based mainly on their contract values and their impacts to the O&G production on the NCS.

In order to minimise development costs and optimise existing infrastructure, some fields are jointly developed. Alvheim FPSO was installed to initially serve as the production platform for the Alvheim development. Later, Marathon developed Volund which was also tied to the Alvheim FPSO. Afterwards, Norsk Hydro also used the Alvheim FPSO for its Vilje development (now, Vilje is also operated by Marathon). Since the fields are interconnected and located close to each other, having one subsea asset maintenance contract for those fields is a cost-effective solution. The fields which are jointly developed are not necessarily operated by the same O&G company. Dong developed Oselvar by tying it to the Ula platform operated by BP. The Statoil-operated Aasta Hansteen will have its gas production transferred to a Shell-operated gas plant at Nyhamna. Thus, joint subsea asset maintenance contract among O&G companies is more critical than ever before.

Installation of subsea assets, in particular subsea processing systems has an increasing trend. Subsea processing systems enable small fields to be tied into larger facilities and field centres, which extends the life and increases the yield of existing platforms and infrastructure [13]. Some subsea processing systems which have been or will be installed are 1,250-ton Subsea Separation, Boosting and Injection (SSBI) station for Tordis, 5,500-ton subsea gas compression system for Åsgard, and 1,100-ton wet gas compression system for Gullfaks. Consequently, subsea asset

Table 1 Overview of 15 subsea asset installation projects on the NCS

Subsea installation project	Location and water depth	Main scope of work	Main subsea assets
Alvheim, Volund, Vilje	Central part of the North Sea; 120–130 m	Tie-back to Alvheim FPSO, gas export to the SAGE	Manifolds, flowlines
Skinfaks/Rimfaks IOR	Northern part of the North Sea; 130–140 m	Install gas lift infrastructure from Rimfaks to Skinfaks	Manifolds, flowlines
Snøhvit	Barents Sea; 310–340 m	Tie-back to 140-km-away onshore processing plant	Manifolds, flowlines, MEG system, power and control from shore
Tyrihans	Norwegian Sea; 285 m	Tie-back to Kristian and Åsgard platforms	Manifold, flowlines including BuBi®, DEH
Tordis IOR	Northern part of the North Sea; 200 m	Install subsea separation, boosting and injection (SSBI) station	SSBI station, tie-in manifold, flowlines
Skarv and Idun	Norwegian Sea; 350–450 m	Tie-back to Skarv FPSO, gas export to the ÅTS	Manifolds, flowlines, DEH
Goliat	Barents Sea; 360–400 m	Tie-back to Goliat FPSO	Manifolds, flowlines, DEH
Oselvar	Southern part of the North Sea; 72 m	Tie-back to Ula platform	Manifold, flowlines
Marulk	Norwegian Sea; 370 m	Tie-back to Norne FPSO	Manifold, flowlines including PiP
Skuld	Norwegian Sea; 360 m	Tie-back to Norne FPSO	Manifolds, flowlines including PiP, DEH
Åsgard gas compression	Norwegian Sea; 300 m	Install a subsea compression facility	Subsea compressors, tie-in manifold, flowlines
Knarr	Northern part of the North Sea; 130 m	Tie-back to Knarr FPSO, gas export to the FLAGS	Manifold, flowlines including bundle
Gullfaks wet gas compression	Northern part of the North Sea; 135 m	Install a subsea wet gas compression facility	Subsea wet gas compressors, flowlines
Martin Linge	Northern part of the North Sea; 120 m	Tie-back to a jacket platform, oil export through a FSO, gas export to the FUKA	Flowlines, power and control from shore
Aasta Hansteen	Norwegian Sea; 1,300 m	Tie-back to a Spar platform, gas export through the Polarled	Manifolds, flowlines including SCR

intervention is needed more than ever before. Furthermore, there may be a need to have a specialized subsea asset maintenance contract for subsea processing systems.

Subsea technology is increasingly used to develop fields in extreme environments and remote locations [9]. Consequently, from technology standpoint, the increasing complexity of subsea assets makes subsea asset maintenance more technically challenging [16]. The increasing use of subsea assets drives more utilization of IT to enable remote operation. By enabling remote operation, some offshore works can be performed onshore, which can significantly reduce operational expenditures [3]. Production in Snøhvit field is controlled remotely from a control room onshore at Melkøya through fibre-optic cables. Martin Linge development will have its offshore production controlled remotely from shore (Stavanger). Thus, the subject of subsea asset maintenance also now includes high bandwidth subsea communication system.

Another increasing technological complexity is the use of flowlines with heating system, which is driven by deeper water depth and significantly varying water depths of one offshore production system. Consequently, subsea asset maintenance also needs to be able to maintain the subsea heating system to support flow assurance. From an operational standpoint, one offshore production system development may use both diving and non-diving methods. Diving offers quicker response and can be a cheaper method, but has limitations with respect to scope of work and water depth. Meanwhile, non-diving methods have the technical capabilities to perform wider scope of work and are able to work in very deep water. Thus, both diving and non-diving will be continuously used for subsea asset maintenance.

Since O&G industry has become the most important foundation for the Norwegian economy [8], there has been a constant pressure to make large O&G discoveries [11]. Promising seismic data with potential large discoveries, new technology development, and the Skrugard oil discovery in 2011 have contributed to more active development in the Norwegian Sea and the Barents Sea [10]. This area has harsher weather and less-developed infrastructure than the North Sea, which are technically challenging for offshore operations. Moreover, the Barents Sea is an environmental-sensitive area, and hence the offshore operations in this area should be performed more carefully.

2.2 *Success Criteria in the Future Subsea Asset Maintenance on the NCS*

In order to succeed in future subsea asset maintenance on the NCS, subsea contractors need to recognize its success criteria. The findings described in Sect. 1.2.1 are mapped into the success criteria by using [9] which identifies several influencing factors affecting the installation and maintenance of offshore production systems. The influencing factors are legislation, geographic location, logistics, environment, technology, costs, external issues, HSEQ, and experience. HSEQ, legislation and external issues are not discussed in this paper. Geographic location refers to local presence and local content, which are also not discussed in this paper. Based on the study done in this paper, the success criteria of the future subsea asset maintenance on the NCS are described below.

i. *Logistics—reliable logistics in the north of the NCS*
   More active development in the Norwegian Sea and the Barents Sea which have relatively less-developed infrastructure than in the North Sea creates an increasing need to have reliable logistics to support subsea asset maintenance in the area. The logistics reliability which is combined with the offshore spread's availability and capability are essential to ensure that high quality subsea asset maintenance can be delivered and even with a possible short lead time.
ii. *Environment—high operability in harsher weather and with increasing focus on environmental aspect*
   Increasing numbers of subsea assets and a wider area of operation on the NCS create a need to have an offshore spread that has high operability and can withstand harsher weather than that which the spread typically faces in the North Sea. Additionally, more active development in the environmental-sensitive Barents Sea pushes O&G companies to have more focus on the impacts of offshore production to the environment.
iii. *Technology—technical capabilities to overcome increasing technological complexity*
   In order to respond to increasing challenges in offshore production, offshore production systems are more dependent on technology than before. Subsea asset maintenance should be equipped with appropriate technology to maintain various more-complex-technology subsea assets. There may also be a need to establish stand-alone contracts to maintain several technology-breakthrough subsea assets, in particular subsea processing systems.
iv. *Costs—strive for cost efficiency*
   Due to increasing numbers of subsea assets, the need for cost efficiency will be continuously enforced. Several fields are jointly developed and their subsea asset maintenance is managed through the same contract. Furthermore, several jointly developed fields are not owned by the same O&G company, which opens an opportunity for several O&G companies to establish a joint subsea asset maintenance contract. The cost efficiency initiative may also drive more frequent involvement of subsea asset maintenance spreads for incremental field development.
v. *Experience and competence—experienced and competent subsea asset maintenance spreads*
   Due to increasing technical complexity, sufficient experience and competence are needed more than before. The experience and competence should be able to streamline the maintenance strategy carried over from subsea installation phase to ensure that the strategy and operation of subsea asset maintenance are in line with the O&G company objectives. Thus, there may be a need to have

an integrated subsea asset installation and subsea asset maintenance, i.e. both phases are performed by the same subsea contractor.

3 Life of Field Concept: Overview and Evaluation

Life of Field (LoF) refers to services offered by subsea contractors to O&G companies once a field has started its production. Based on scope of work capabilities, the services of LoF can be categorized into three categories [15]:

i. integrity Assurance,
ii. intervention, and
iii. incremental Capital Expenditure (Capex).

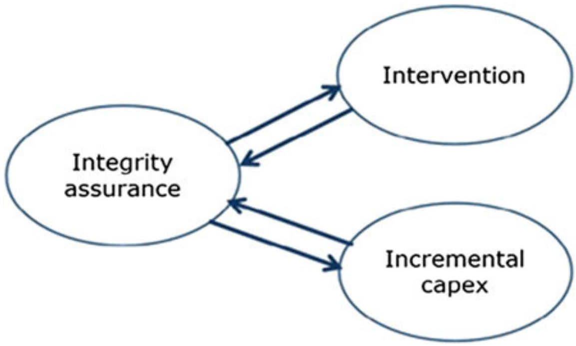
Integrity assurance refers to planned actions to assure the structural and operational integrity of subsea assets. The services of integrity assurance include inspection and planned maintenance operation performed by Autonomous Inspection Vehicle (AIV), Remotely Operated Vehicle (ROV) or divers.

Based on the input from the integrity assurance team, there may be a need for intervention. The term intervention refers to unplanned actions to mitigate an identified failure or anomaly that may have adverse impact to the integrity of subsea assets. An example of intervention service is scale squeeze operation where chemicals are injected into the well from a LoF vessel to dissolve and remove unwanted scale which can block hydrocarbon production flow.

The third LoF category is incremental capex whose main idea is to offer LoF spreads to do incremental development in a particular field. The LoF spread usually has been maintaining the field in 24/7 basis. Thus, the team has better knowledge regarding the field and the associated subsea assets, and hence is able to execute projects which fit better the ongoing operation (Fig. 2).

The three LoF categories are essentially interconnected. Therefore, the full benefits of LoF services will be exploited if the services are integrated. For

Fig. 2 Interconnection among LoF categories



example, to ensure that a rigid pipe system functions well, the subsea contractor first needs to do pipe inspection (which is an integrity assurance service). If a leak is found on the pipe, the mitigation may be having the contractor do pipe welding (which is an intervention service). The mitigation may also be having the contractor procure and install a new pipe section (which is an incremental capex service).

3.1 Inspection, Maintenance and Repair (IMR)

Life of Field is traditionally associated to the industrial terminology inspection, maintenance and repair (IMR). Unlike the definition according to the European Standards as mentioned in Sect. 1, Maintenance in IMR has a narrower context and refers to periodic maintenance. Meanwhile, for unplanned maintenance, industry usually uses the terminology Repair.

As mentioned in [14], IMR is a subsea emergency and fast emergency corps. The IMR spread is expected to be readily available and cost conscious. This philosophy is the main reason why IMR contracts on the NCS are usually established as long-period frame contracts and the IMR vessels are equipped with only light construction capabilities.

All IMR vessels in Table 2 are capable of operating Module Handling System (MHS). This method offers launch and recovery of modules through moonpool which has high tolerance to adverse weather. Thus, vessel with MHS can have higher operability, in particular to withstand harsh weather on the NCS.

As shown in Table 2, the vessels for the current Statoil IMR contracts have main crane with lifting capacity up to 150 tons. This main crane will not be able to handle mid-heavy modules up to 250 tons. For example, manifold for Alvheim weighs 170 tons and the heaviest module of the SSBI station for Tordis IOR weighs 250 tons. Consequently, the current IMR vessels are not always suitable for

Table 2 Vessel technical specification for the current Statoil IMR contracts

Parameter	Rem Ocean	Seven Viking	Edda Fonn	Edda Fauna
Main crane's capacity	150 tons, up to 2,000 m	135 tons, up to 2,000 m	100 tons, up to 2,000 m	100 tons, up to 2,000 m
Deck area (m^2)	1,020	830	700	610
ROV	2 WROV, 1 OROV	2 WROV, 1 OROV	1 WROV, optional additional WROV/ OROV	2 WROV, 1 OROV
MHS	Yes	Yes	MHS interface	Yes
Scale squeeze	No	Yes	No	Yes

incremental capex service. The current common approach for incremental capex service is using normal construction vessel spread, which is much more expensive than the LoF spread.

The IMR model also makes a clear distinction between subsea asset installation and subsea asset maintenance. Subsea contractor that installs a particular subsea asset is not necessarily the one that will maintain the asset. DeepOcean, the current market leader of subsea asset maintenance on the NCS, in fact traditionally does not perform main installation of subsea assets on the NCS.

3.2 The Fitness of LoF to the Future Subsea Asset Maintenance on the NCS

The analysis in Sect. 2.2 has mapped the success criteria of the future subsea asset maintenance on the NCS. The findings of the LoF analysis will be compared against the success criteria to assess the fitness of LoF to the future subsea asset maintenance on the NCS.

i. *Logistics—reliable logistics in the north of the NCS*
   In Norway, Subsea 7 has logistics bases in Dusavik, Kristiansund and Oslo. Dusavik lies adjacent to southern and centre parts of the North Sea, which makes it a good base to support offshore operations in the North Sea. The Kristiansund base lies in a good location to support offshore operations in some areas of the North Sea and the Norwegian Sea. Meanwhile, the Oslo base is located in south-eastern Norway. Due to more active field development in the Norwegian Sea and the Barents Sea, there may be a need to have additional logistics base in the far north of Norway. Since subsea asset maintenance is usually managed through a long-term frame contract, the offshore operations can also be supported through the bases managed by the O&G company. For example, Statoil has a base in Harstad, which is in a good location to support offshore operations in the Norwegian Sea and the Barents Sea.
ii. *Environment—high operability in harsher weather and with increasing focus on environmental aspect*
   All vessels for the current Statoil IMR contracts are capable of operating MHS, which enables high operability on the NCS along the year. Additionally, the ROV and AIV operated by the subsea contractors on the NCS are generally able to operate in deep water and harsh environment. The impact to the environment should always be taken into account in all off-shore operations performed by subsea contractors since environmental damage may result in a fiscal penalty and negative impact to the company reputation. However, this particular sub-issue is not discussed further in this paper.
iii. *Technology—technical capabilities to overcome increasing technological complexity*

Advancement in technology in vessel technical specifications and onshore engineering capabilities enable subsea contractors to perform various challenging subsea works successfully. Technological capabilities can be built in house or developed through partnership with a number of technology providers.

iv. *Costs—strive for cost efficiency*
LoF vessels are designated mainly to continuously maintain subsea assets. Thus, cost efficiency is one the LoF philosophies. For example, crane ratings are one of the main cost drivers of vessel's day rate. The LoF vessels for the current Statoil IMR contracts have offshore crane with lifting capacity up to 150 tons. This is below the capability of medium construction vessel such as Skandi Seven which can lift up to 250 tons. Consequently, LoF vessels are able to offer lower cost than normal construction vessel. However, the main crane's low capacity makes the LoF vessels not always suitable for incremental capex service.

v. *Experience and competence—experienced and competent subsea asset maintenance spreads*
Subsea contractor that installs a particular asset has experience and competence advantages to also maintain the asset. However, the current IMR model makes a clear distinction between subsea asset installation and subsea asset maintenance. Subsea contractor that installs an asset is not necessarily the one that will maintain the asset. Consequently, the LoF capabilities are not optimally utilised yet.

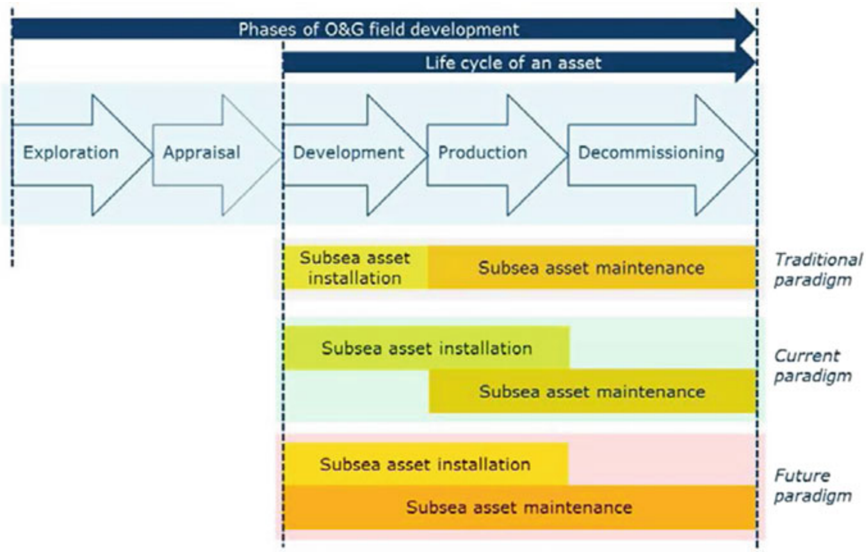


Fig. 3 Paradigm changes of subsea asset installation and subsea asset maintenance

4 Improvement Potential

The first improvement potential can be obtained by changing the current paradigm of LoF contract practice which tends to associate LoF to the IMR model. There is a need to establish a LoF model which accommodates continuous maintenance process to O&G field development from the Development to the Decommissioning phase. This ensures a 'cradle to grave' or a life cycle approach. The life cycle approach facilitates continuous improvement in all steps during the life cycle of an asset [4]. It will extend the lifetime and maintain the effectiveness of the asset [12], which subsequently will improve the asset capability to better support company objectives [7]. The new LoF model gives a framework to enable experience and competence developed during the Development phase to be optimally applied during the Production phase. This may imply that a subsea contractor that installs a particular subsea asset is the one that will maintain the asset.

From technology standpoint, the future paradigm may imply that the LoF vessels need to have offshore crane with lifting capacity up to 250 tons. This mid-heavy capacity will make the LoF spread more suitable for incremental capex service, and hence it may offer better cost structure for the overall O&G field development in a particular field (Fig. 3).

In order to further improve the fitness of LoF to the future subsea asset maintenance on the NCS, subsea contractors need to establish a logistics base in the far north of Norway. The base is intended to better support offshore operations in the Norwegian Sea and the Barents Sea. There has been also a constant pressure to increase the recovery rate from the fields on the NCS. This makes subsea intervention more critical than before. Consequently, intervention capability such as scale squeeze should be a standard technical specification of the LoF vessels.

5 Conclusion

Subsea solutions have a defining success on the future of offshore oil and gas activities. Due to challenging production conditions and complexity of subsea technologies, the solutions that are provided need to be smarter and integrated. More and more integrated solutions are seen applied in various assets during the last few years. Life of Field (LoF) is a modern solution with a greater application potential both in current and future asset development and operations. Based on a collaborative project, this paper reviewed and evaluated the fitness of the LoF concept with respect to the forthcoming demand of the offshore sector. It shed some light on the core features expected of similar solutions for advanced research on subsea maintenance solutions as well as novel industry wide applications.

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Research and Development: Driving Innovation in a Declining Mining Industry

E. Theron and P.J. Volk

Abstract Research and development in mining and technology sectors play an important role in the innovation process and is also a key factor in developing new competitive advantages. Currently the focus of research and development in the mining sector is on activities downstream of the actual extraction of the raw materials. The main focus of these activities is on the development of technologies for the clean-up of historic mining wastes. However, the declining grades of mined ore and increasing financial pressure on mining industries suggests that research and development should be more focused on technologies to extract the mineral ore more efficiently and effectively. This paper compares the research and development investment in the mining sector to similar investment in four other sectors.

Keywords Research and development · Mining assets · Innovation

1 Introduction

The mining industry in South Africa is currently the fifth largest mining industry in the world [1]. As a result, the contribution of the mining industry to the development and positive growth of the South African economy is considerable. During the past few years the mining industry has experienced increasing pressure to extract mineral ores more profitably from progressively lower-grade ore bodies, accompanied by rising operating costs, increasingly challenging safety and environmental issues. There exists an urgent demand for high level engineering and scientific competence within the mining terrain.

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_30

Innovation in the mining industry has historically been focused on cost reductions as the primary mechanism for business improvement [2]. The inclination to focus on increasing the size and longevity of production equipment offers short-term incremental benefits, however it also limits innovation in the long-term as longer lasting equipment limits the supply from manufacturers. R&D expenditure is imperative in finding solutions to ever-diminishing and complex ore-bodies, environmental impacts, and energy and water constraints. Similarly, R&D expenditure in the mining industry should drive innovation and shift the focus from inflexible short-term cost reductions to long-term value creation. This paper aims to highlight the lack of R&D spending in the mining industry. The R&D expenditure in the four most innovative industries will be studied and compared to that of the mining industry. R&D expenditure will be calculated as a percentage of the revenue of the relative industry and will then serve as a common comparator of R&D expenditure in the different industries. The effect of the R&D expenditure will then be studied against the relative Price-Earnings (PE) ratios with the purpose of identifying important trends.

2 Research and Development (R&D) and Innovation

According to the European Commission, the most critical factors that will determine the well-being of Europe's future wealth are the following: highly skilled human capital, investment in research and development, market conditions conducive to innovation, and faster take-up of new technologies [3]. R&D is the part of a commercial company's activities that are focused on innovation, concerned with applying the results of scientific research to the development of new products/services and/or to improve existing ones [4].

According to the Oslo Manual, innovation is the development and implementation of new or substantially improved goods, services and/or processes, or a new marketing or organizational methods in business practices, workplace organization or external relations [5]. From the above two definitions it is apparent that innovation is dependent on investment in R&D, however an increased investment in R&D does not necessarily lead to an increase in innovation. R&D is only a catalyst in driving innovation, there are many other factors that influence innovation such as; access to open information sources, acquisition of knowledge and technology and co-operation with other firms or public research institutions [5]. R&D in any industry drives innovation which in turn leads to the development of new technologies and consequently, new competitive advantages.

In many businesses, R&D is considered a high risk investment and business owners would rather invest in capital employed within the business itself. However, according to the European Association of Research and Technology Organizations (EARTO) [6], investment in R&D produced a return that was roughly three times that of capital investment. Businesses that are very risk-averse focus more on capital investment and the expansion of the current capacity, whereas for the purposes of future growth, the aim of the business should be to produce new, innovative technology and exploit it. “It has been apparent for at least a century that future economic progress will be driven by the invention and application of new technologies” [7].

3 R&D Investment in the Four Most Innovative Industries

As mentioned before, there exists a strong correlation between R&D and innovation. Industries that rely on the constant research and development of new products, processes, services and/or techniques are highly dependent on innovation. These industries mainly rely on the establishment of patents and as a result, these industries have a very high investment rate into R&D. According to The Global Innovation 1000 study done annually by Booz & Company, the most innovative companies are those in the computing and electronics, pharmaceutical, software and internet and the automotive industries [8]. Therefore, the R&D expenses as well as the PE ratios of three companies in each of the before mentioned industries will be studied in moderate detail and compared to that of the mining industry in the next section.

R&D expressed as a percentage of the revenue for a specific business is referred to as the R&D intensity. The R&D intensity is a good indicator of the level of effort dedicated to generating new knowledge such as future product and process improvements, while simultaneously maintaining the current market share and improving operating efficiency [9]. R&D intensity is therefore used to gauge the relative importance of R&D investments across different industries as well as among companies within the same industry. The relative R&D figures used in this paper were obtained from the respective company’s annual reports.

The PE ratio represents a valuation ratio of a company’s per share earnings compared to the current share price. Thus, the PE ratio represents the amount earnings investors are willing to pay for a share. Therefore, a higher PE ratio indicates greater expected future gains as a result of some perceived growth opportunity and/or reduced risk and/or some competitive advantage [10]. Therefore, the PE ratio is used to analyze industries and companies within the same industry to determine those with the highest future value creation potential. The PE ratios for the companies in the pharmaceutical, automotive, computing and electronics and software and internet industries were obtained from their respective historical financial data on Y-Charts, a financial terminal on the web [11]. The PE ratios for the companies in the mining industry were obtained from their respective historical data on the London Stock Exchange [12].

3.1 R&D Investment in the Pharmaceutical Industry

Companies in the pharmaceutical industry have an exceptionally high reliance on innovation. The primary purpose of medical innovations is to help patients live longer, healthier and more productive lifestyles [13]. Therefore, the development of new techniques and technologies as well as new products, processes and/or services are the primary focus of the pharmaceutical industry. As a result, the R&D intensity is of the highest compared to other industries. For the purposes of this article the pharmaceutical industry will be generalized by analyzing only the data obtained from the following three pharmaceutical companies; Johnson & Johnson (Pty) Ltd, Pfizer and GlaxoSmithKline (GSK).

In the following table the total revenues as well as the total R&D expenditure for 2010–2012 are listed. In the second last column the R&D intensity is illustrated, this common figure will be used to compare the R&D investment in the three different pharmaceutical companies. The PE ratio for the respective pharmaceutical companies are illustrated in the last column. The PE ratio represents a valuation ratio of a company's per-share earnings compared to the current share price.

From the data represented in Fig. 1, the PE ratio increases with an increase in the R&D intensity for both Johnson & Johnson and Pfizer. This suggests that there exists some proportional relationship between the R&D intensity and the PE ratio. However, the opposite is true for the data representing GlaxoSmithKline (GSK). In the pharmaceutical industry the research and development process involves numerous trials to investigate the efficiency and safety of potentially new treatments, thus even though money is invested into R&D, the effect thereof on the PE ratio can only be noticed in later years. In 2011 GSK experienced a spike in its PE ratio, this was as a result of significantly lower legal charges and resulted in a larger

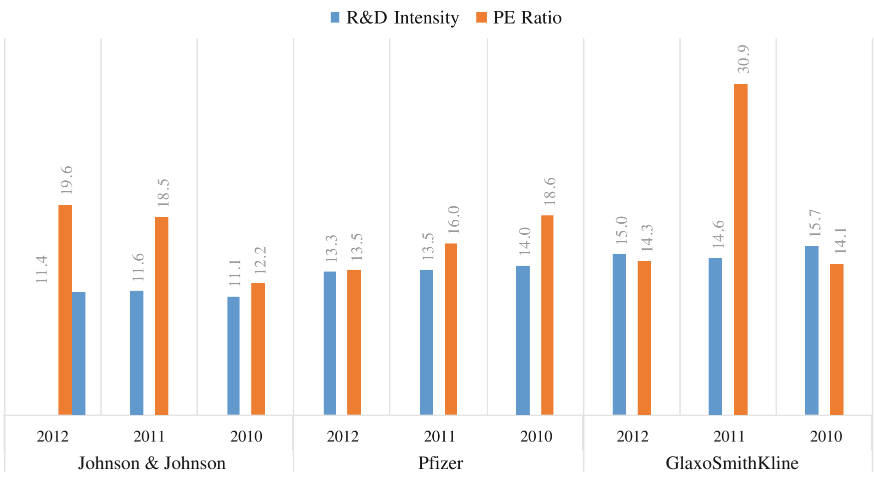

Fig. 1 Comparison of R&D intensity and PE ratios in the pharmaceutical industry

Table 1 Net revenue, R&D expense and PE ratio in the pharmaceutical industry

Industry	Company	Year	Net revenue (Million USD)	R&D expenses (Million USD)	R&D intensity	PE ratio
Pharmaceutical industry	Johnson & Johnson	2012	67,224	7,665	11.4	19.6
		2011	65,030	7,548	11.6	18.5
		2010	61,587	6,844	11.1	12.2
	Pfizer	2012	58,986	7,870	13.3	13.5
		2011	67,425	9,112	13.5	16.0
		2010	67,057	9,392	14.0	18.6
	GlaxoSmithKline	2012	43,875	6,587	15.0	14.3
		2011	45,462	6,655	14.6	30.9
		2010	47,131	7,399	15.7	14.1

earnings per share (EPS) value [14]. Also in 2011 GSK had a very high delivery of sales from newly launched products, thus increasing the overall net revenue of the company and resulting a very high PE ratio (Table 1).

3.2 R&D Investment in the Automotive Industry

The automotive industry consists of a large number of organizations and companies that specialize in the design, development, manufacturing, marketing and selling of motor vehicles. As a result, the automotive industry is one of the world's largest economic sectors. Innovation in the automotive industry is becoming one of the primary focuses. Consumers support companies that introduce new technologies to the market and that prioritize fuel efficiency, safety and connectivity as their main focus areas [15]. For the purposes of this article the automotive industry will be generalized by analyzing only the data obtained from the following three main automotive companies; Toyota, Volkswagen and Ford.

In the following table the total revenues as well as the total R&D expenditure for 2010–2012 are listed. In the second last column the R&D intensity is illustrated, this common figure will be used to compare the R&D investment in the three different automotive companies. The PE ratios for the respective automotive companies are illustrated in the last column.

From the data depicted in Fig. 2, the PE ratio increases with an increase in the R&D intensity for both Toyota and Volkswagen. This again implies that there exists some proportional relationship between the R&D intensity and the PE ratio. Ford had a constant R&D intensity in 2010 and 2011, however the PE ratio

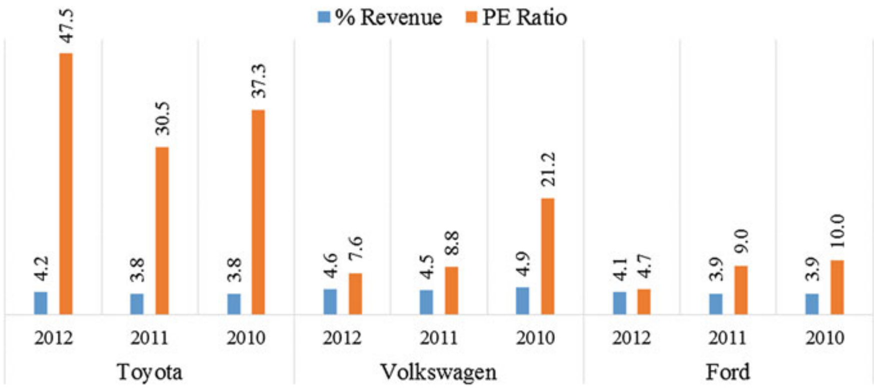

Fig. 2 Comparison of the R&D intensity and PE ratio in the automotive industry

decreased. During 2012 the R&D intensity increased and the PE ratio decreased, this is due to a one-time, non-cash special item from the release of almost all the valuation of the allowance against net deferred tax in the fourth quarter of 2011 [16]. This brought down the PE ratio significantly. Toyota and Volkswagen both experienced a decline in their PE ratios from 2010 to 2011, a result of the economic slowdown following the global recession and accompanied by rising fuel prices and high interest rates. In 2012 Toyota experience a rise in its PE ratio as a result of the continuous cost reduction efforts and also the use of common parts resulting in a reduction of part types. Also, the cost of products sold decreased as a result of the favourable impacts of fluctuations in foreign currency translation rates [17]. Both of these factors contributed to the increase in the PE ratio from 2011 to 2012 (Table 2).

Table 2 Net revenue, R&D expense and PE ratio in the automotive industry

Industry	Company	Year	Net revenue (Million USD)	R&D expenses (Million USD)	R&D intensity	PE ratio
Automotive industry	Toyota	2012	182,119	7,642	4.2	47.5
		2011	186,138	7,157	3.8	30.5
		2010	185,720	7,108	3.8	37.3
	Volkswagen	2012	265,893	12,214	4.6	7.6
		2011	219,885	9,940	4.5	8.8
		2010	175,088	8,635	4.9	21.2
	Ford	2012	134,252	5,500	4.1	4.7
		2011	136,264	5,300	3.9	9.0
		2010	128,954	5,000	3.9	10.0

3.3 R&D Investment in the Computing and Electronics Industry

The computing and electronics industry is characterized by rapid technological advances. Thus, in order to compete successfully in this industry, companies depend heavily on their ability to ensure a continuous flow of competitive products, services and technologies to the market [18]. As mentioned earlier R&D drives innovation and innovation may lead to competitive advantages if the product, service and/or technology is economically viable. For the purposes of this article the computing and electronics industry will be generalized by analyzing only the data obtained from the following three main computing and electronics companies: Apple Inc., IBM, Samsung.

In the following table the total revenues as well as the total R&D expenditure for 2010–2012 are listed. In the second last column the R&D intensity is illustrated, this common figure will be used to compare the R&D investment in the three different computing and electronics companies. The PE ratio for computing and electronics companies are illustrated in the last column.

From the data depicted in Fig. 3, the PE ratio increases with an increase in the R&D intensity for Apple Inc., IBM and Samsung. This again implies that there exists some proportional relationship between the R&D intensity and the PE ratio. However, in 2010–2011 the PE ratio for IBM increased even though the R&D intensity decreased. This increase in the PE ratio was as a result of the growth in the IBM's net income as well as the benefits of its common stock repurchasing program [19]. Samsung experienced a decline in its PE ratio from 2011 to 2012 even though the R&D intensity increased. This is due to the rapid growth of mobile PC sales in 2011 as well as the large global market share the company owns in the semiconductor market [20]. Apple Inc. experienced a decrease in its PE ratio from 2010 to 2012 while the R&D intensity decreased slightly from 2010 to 2011, but remained constant from 2011 to 2012. The decrease in the PE ratio was as a result of the high earnings growth that Apple Inc. experienced during this period [18] (Table 3).

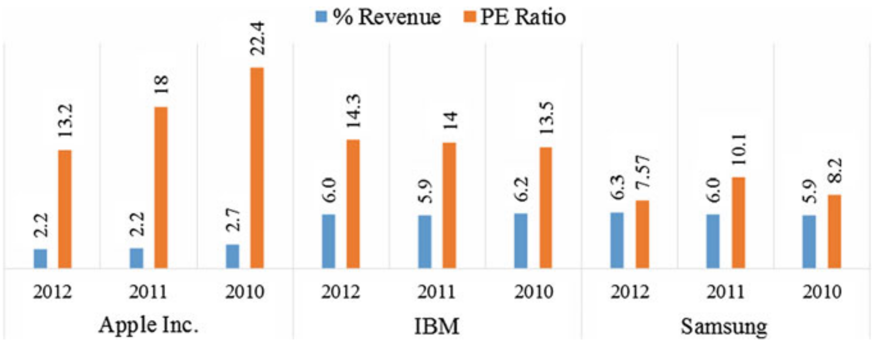

Fig. 3 Comparison of the R&D intensity and PE ratio in the computing and electronics industry

Table 3 Net revenue, R&D expense and PE ratio in the computing and electronics industry

Industry	Company	Year	Net revenue (Million USD)	R&D expenses (Million USD)	R&D intensity	PE ratio
Computing and electronics industry	Apple Inc.	2012	156,508	3,381	2.2	13.2
		2011	108,249	2,429	2.2	18
		2010	65,225	1,782	2.7	22.4
	IBM	2012	104,507	6,302	6.0	14.3
		2011	106,916	6,345	5.9	14
		2010	99,870	6,152	6.2	13.5
	Samsung	2012	187,026	11,741	6.3	7.57
		2011	153,452	9,281	6.0	10.1
		2010	143,806	8,462	5.9	8.2

3.4 R&D Investment in the Software and Internet Industry

Companies in the software and internet industry rely greatly on the research and development of new, technologically advanced products. This process is complex and uncertain and as a result, high levels of innovation and investment is required. For the purposes of this article the software and internet industry will be generalized by analyzing only the data obtained from the following three main software and internet companies; Google, Microsoft and Oracle.

In the following table the total revenues as well as the total R&D expenditure for 2010–2012 are listed. In the second last column the R&D intensity is illustrated, this common figure will be used to compare the R&D investment in the three different software and internet companies. The PE ratio for the respective software and internet companies are illustrated in the last column.

From the data depicted in Fig. 4, the PE ratio increases with an increase in the R&D intensity for Microsoft and Oracle. This again implies that there exists some proportional relationship between the R&D intensity and the PE ratio. However, the opposite is true for the data representing Google. The steady decrease of the PE ratio from 2010 to 2011 is as a result of the strong, sustained earnings growth as well as the decreasing net income [21]. During 2010–2011 Oracle experienced an increase in the R&D intensity; however the PE ratio decreased in this period. The decrease in the PE ratio was as a result of the decline in the hardware revenue segment causing a decrease in the return of invested capital (ROIC) and consequently a decrease in the PE ratio [22]. Microsoft experienced a decline in its R&D intensity as well as its PE ratio in 2011; this decline is due to the decline in revenue in the Windows division as well as the operating loss in the online services sector [23] (Table 4).

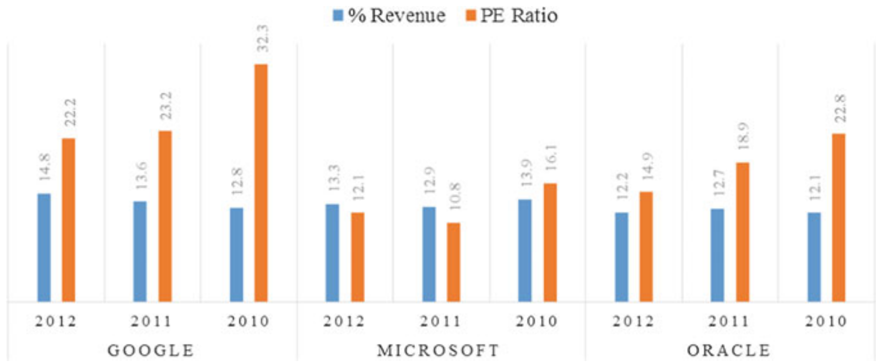

Fig. 4 Comparison of the R&D intensity and PE ratio in the software and internet industry

Table 4 Net revenue, R&D expense and PE ratio in the software and internet industry

Industry	Company	Year	Net revenue (Million USD)	R&D expenses (Million USD)	R&D intensity	PE ratio
Software and internet industry	Google	2012	46,039	6,793	14.8	22.2
		2011	37,905	5,162	13.6	23.2
		2010	29,321	3,762	12.8	32.3
	Microsoft	2012	73,723	9,811	13.3	12.1
		2011	69,943	9,043	12.9	10.8
		2010	62,484	8,714	13.9	16.1
	Oracle	2012	37,121	4,523	12.2	14.9
		2011	35,622	4,519	12.7	18.9
		2010	26,820	3,254	12.1	22.8

3.5 R&D Investment in the Mining Industry

As mentioned earlier, the mining industry in South Africa contributes to the positive growth and development of the economy. In 2012 the mining industry contributed to over 8 % of the Gross Domestic Product (GDP) of South Africa. If the indirect multiplier, as well as the induced effects are included, then the overall contribution to the GDP was more than 17 % [24]. Also during 2012, the mining industry accounted for 19 % of private sector investments and 11.9 % total investment in the economy. Furthermore, the mining industry in South Africa also accounted for 24.7 % of the All-Share Index and 24.4 % of the equities market capitalization of the Johannesburg Securities Exchange (JSE) at the end of 2012 [24]. Apart from contributing to the South African economy financially, according to a recent study by Quantec and the Industrial Development Corporation (IDC) in 2012, the mining industry helped to create 1,365,892 jobs, of which 524,632 were directly employed in the mining industry [1]. From the before mentioned information it is clear that the

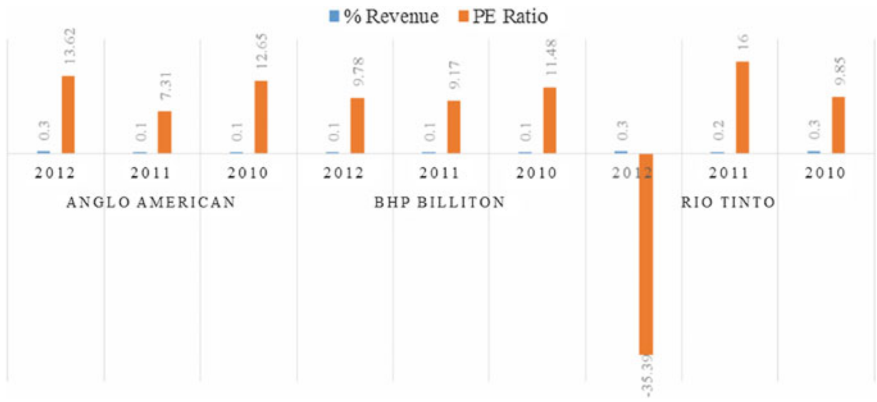

Fig. 5 Comparison of the R&D intensity and PE ratio in the mining industry

South African economy is strongly dependent on the contribution of the mining industry, both directly and indirectly.

In the following table the total revenues as well as the total R&D expenditure for 2010–2012 are listed. In the second last column the R&D intensity is illustrated, this common figure will be used to compare the R&D investment in the three different mining companies. The PE ratio for the respective mining companies are illustrated in the last column.

From the data depicted in Fig. 5, the R&D intensity is very small for all three mining companies compared to those of the other industries. The PE ratio for Anglo American remained at a constant 0.1 for 2010 and 2011, however in 2012 it increased slightly to 0.3. The PE ratio for Anglo American decreased from 2010 to 2011 even though the R&D intensity remained constant. The decrease in the PE ratio was as a result of the decreasing platinum and copper share in the operating profit in addition to the economic slowdown following the global recession and the political unrest in North Africa and the Middle East [25]. BHP Billiton experienced a constant R&D intensity from 2010 to 2012; however the PE ratio decreased slightly from 2010 to 2011 and increased again in 2012. The decrease in the PE ratio was also as a result of the economic slowdown following the global recession as well as the European sovereign debt crisis [26]. Rio Tinto experienced a decrease in R&D intensity from 2010 to 2011; however the PE ratio increased during this period. The increase in the PE ratio was as a result of the significant increase in the full year dividends, reflecting confidence in long-term outlook [27]. During 2011–2012 the R&D intensity increased again whereas the PE ratio experienced a sharp decline producing a negative value. The decrease in the PE ratio was due to the net loss made during 2012 owing to impairments relating to the aluminium businesses and the coal assets in Mozambique [28] (Table 5).

Table 5 Net revenue, R&D expense and PE ratio in the mining industry

Industry	Company	Year	Net revenue (Million USD)	R&D	expenses (Million USD)	R&D
intensity	PE ratio					
Mining industry	Anglo American	2012	28,761	80	0.3	13.62
		2011	30,580	38	0.1	7.31
		2010	27,960	29	0.1	12.65
	BHP Billiton	2012	72,226	75	0.1	9.78
		2011	71,739	74	0.1	9.17
		2010	52,798	65	0.1	11.48
	Rio Tinto	2012	50,967	129	0.3	−35.39
		2011	60,537	148	0.2	16
		2010	55,171	187	0.3	9.85

4 Comparing the Mining Industry to the Four Most Innovative Industries

In order to compare the data representing the four most innovative industries in section three to the mining industry data in section four, the following two graphs were constructed. Figure 6 represents the average R&D invested as a percentage of the revenue for the different industries in 2010, 2011 and 2012, whereas Fig. 7 represents the average PE ratios for the different industries in 2010, 2011 and 2012.

From the data depicted in Fig. 6, the average R&D intensity in the mining industry is significantly lower than the R&D intensity in the other industries. As mentioned earlier, there exists some proportional relationship between the R&D intensity and the PE ratio. Comparing the data in Fig. 6 to the average PE ratios in Fig. 7 reveals that a higher R&D intensity results in a higher PE value, except for the data representing the automotive industry. The average PE ratio for the automotive industry is higher than that of the pharmaceutical industry even though the average R&D intensity in the automotive industry is substantially lower than that of the pharmaceutical industry. The high average PE ratio in the automotive industry is due to Toyota Motor Corporation's unusually high PE ratio, refer to Fig. 2.

The proportional relationship between the R&D intensity and the PE ratio in Figs. 6 and 7 above highlight the lack of R&D investment in the mining industry. As mentioned earlier, R&D investment drives innovation and innovation leads to the development of new technologies, products and services. Most of the R&D in the mining industry has been concentrated on the better understanding of where to mine i.e. improvements regarding exploration and project study costs. The mining industry has been very slow to evolve in terms of innovation and the development of new mining technologies for the actual extraction of the mineral ore [29].

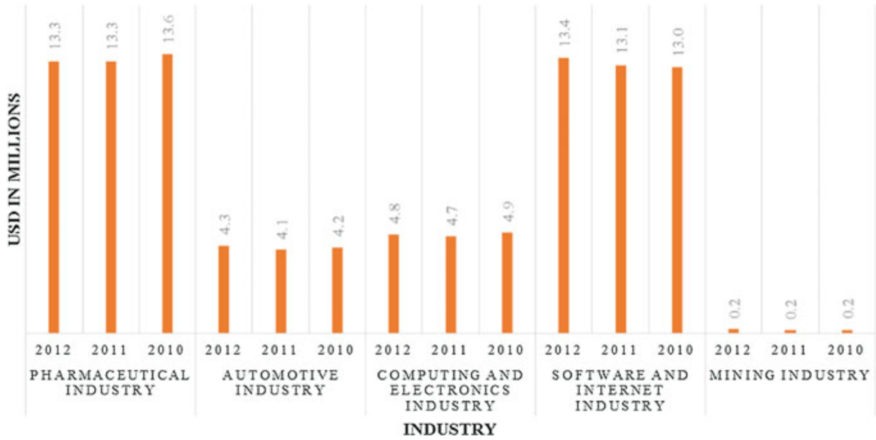

Fig. 6 Average R&D intensities for 2010, 2011 and 2012

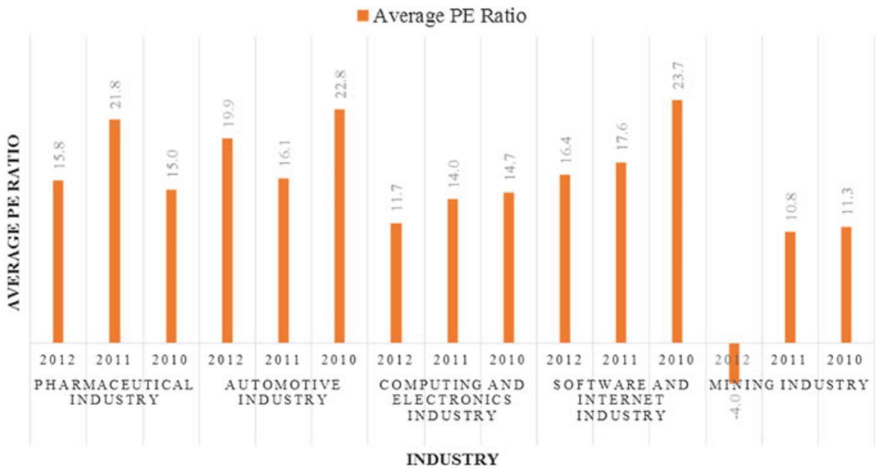

Fig. 7 Average PE ratios for 2010, 2011 and 2012

The capital intensive nature of the mining industry is the reason most mining companies are either stock-listed or government owned. The slow pace of innovation may therefore be a consequence of the lack of interest of the owners of the mining companies into fundamental research and development. Mining by definition is regarded as a marginal business and mining products are commodities sold at very small margins. Thus, spending large amounts of capital on research and development projects with low probability seems to be a waste of money. Its capital-intensive nature, as well as low commodity prices, are only two of the underlying reasons the mining industry is innovating at a much slower pace than that of the pharmaceutical, automotive, computing and electronics and software and internet industries.

According to Deloitte, an audit and consulting firm, the survival of the current volatile commodity markets depends on innovation and structural changes [30]. In an article by Clareo and Partners [2] it is noted that the lack of innovation in the mining industry is the result of a historically collective focus on cost reduction as the primary focus of the business improvement strategy. It also states that risk taking in the mining industry is discouraged, thus resulting in very low R&D spending compared to other industries [2]. The CEO of Mintek, Abiel Mngomezulu, noted that R&D spending is crucial in finding solutions to the declining and complex ore-bodies, energy and water constraints, and environmental impacts [31].

5 Conclusion

Depleting reserves and declining ore grades pose a challenge to the sustainability of the mining industry and calls for research and development into new and safer mining technologies, extraction methods and metallurgical techniques.

One possible solution to increase the interest of mining companies into R&D investment is to establish an organization consisting of a group of major mining companies that supports a mining incubator with a seed fund. The sole purpose of the seed fund is to invest in start-up mining technology companies. This would encourage entrepreneurs to develop their business ideas as they would have access to sufficient capital, knowledge and networks. This will also allow the R&D risk to be spread across a number of different projects. Moreover, it will enable the mining companies to enlarge their stake in any of the participating technology companies developing technology that is specific to their interests.

It can therefore be concluded that the R&D investment in the mining industry is not sufficient enough to sustain the industry into the foreseeable future. There exists a demand for new, innovative and safer technologies for the extraction of the ever-diminishing mineral ores, environmental impacts and, water, energy and emission constraints. In addition, there is also a demand for innovation in sustaining the financial pressure from low commodity prices, global trade and ever-fluctuating currencies.

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The Role of Maintenance, Repair, and Overhaul (MRO) Knowledge in Facilitating Service Led Design: A Nozzle Guide Vane Case Study

L.E. Redding, Christopher J. Hockley, R. Roy and J. Menhen

Abstract In order to improve the availability and cost effectiveness of products over their service life there is a need to improve levels of service knowledge and provide better linkages between that knowledge, the engineering designers, and those providing 'through-life' engineering services and maintenance support. This paper considers what is meant by both design knowledge and service knowledge before offering definitions which are grounded in the literature that will underpin the development of the research in this area. How service knowledge obtained during maintenance, repair and overhaul might be used to increase a product's availability for use in service is considered using a Gas Turbine High Pressure Nozzle Guide Vane as an example case study. It is chosen as it is a complex product using state of the art materials and offers design and manufacturing challenges that are informed by service performance. A greater understanding of the required content, drivers, and inhibitors relative to service knowledge informed design is established together with how service driven design knowledge might be better informed. The paper proposes that existing service knowledge can be used to inform the design of selected complex manufactured components such as those found in aero-engines. A system architecture or framework for a 'design for service' programme which would facilitate greater whole-life component availability, reduced costs due to downtime and potentially much leaner logistics is proposed.

Keywords Design for service · Servitization · Service knowledge

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_31

It is concluded that in the future, there is the ability to develop systems and algorithms which have the ability to apply usage and maintenance knowledge, thereby promoting a greater understanding and characterisation of degradation mechanisms and to use this information to proactively inform the design process.

1 Introduction

The ‘servitization’ of manufacturing organisations is well documented in the literature [1–3]. As organisations are exposed to the twin drivers of global competition and the requirement to provide sustainable solutions [4] relative to both product and process one sees the emergence of Product-Service Systems (PSS) and an alternative business paradigm [5–8]. This has seen the increasing requirement to develop aligned product support and asset management strategies which span the whole life-cycle of the manufactured product [9–12]. Underpinning all of these initiatives is the role of applied technology, systems, and data harvestings techniques which are used to acquire product condition, usage data, degradation status and mechanisms, and service history. The data acquired can then offer information relative to the product which if used appropriately can generate knowledge of use, failure, and required remaining ‘in service’ life.

Data obtained from Integrated Vehicle Health Management (IVHM) generic applications [13, 14], typically Condition Based Maintenance (CBM) [15–17], and Health and Usage Monitoring (HUMS) [18, 19], together with data which is, or could be obtained from the maintenance, repair, and overhaul (MRO) facilities within the service delivery system and infrastructure offers immense potential to improve the products availability for use throughout its life-cycle. Recognition of this is well documented in the ‘Asset Management’ (AM) [20–22], ‘Product life-cycle Management’ (PLM) [23–25] and the emerging ‘Through-life Engineering Services’ (TES) [26–28] literature.

This paper presents ongoing research which seeks to understand how service knowledge can be used to inform design thus enabling the reduction of mean time to failure thereby increasing product availability. To gain this understanding a case study method is applied centred on the design, manufacture and the service support of an aero-engine component, namely a high pressure nozzle guide vane (HPNGV).

2 Research Methodology

In seeking to gain a more comprehensive understanding of the role of service knowledge when used to inform design the research sought to identify a high value manufactured component which was part of complex assembly/product, which should it fail, would have a major impact to the assembly’s availability for use and thus revenue. Within the lens of manufacturing organisations who compete by offering high levels of service in support of their manufactured products (i.e. availability contracting) much is found within the literature relating to the aerospace sector. Typically gas turbines (aero-engines) manufactured by leading organisations (GE, Rolls Royce, and Pratt and Whitney) feature heavily as high risk items to the manufacturer's revenue should they fail. To focus this study the High Pressure Nozzle Guide Vane (HPNGV) was selected as it is a complex product which exhibits a state of the art application relative to materials, design, and production/ service methods (Fig. 1).

The aim of the research presented in this paper is to: define what is meant by design knowledge and service knowledge relative to through-life engineering services in the context of the through-life service support offered by OEM's relating high pressure nozzle guide vanes, and to investigate the role of service knowledge as obtained during maintenance repair and overhaul (MRO) in informing the design of HPNGV's thereby increasing the product's availability for use.

In order to achieve the research aim several questions are presented which serve as way marks to achieving the aim. Namely:

i. What is knowledge in the context of this research?
ii. What is meant by design knowledge in the context of this research?
iii. What is meant by service knowledge in the context of this research?
iv. How can service knowledge obtained from the MRO function inform the engineering design content and process for the HPNGV?

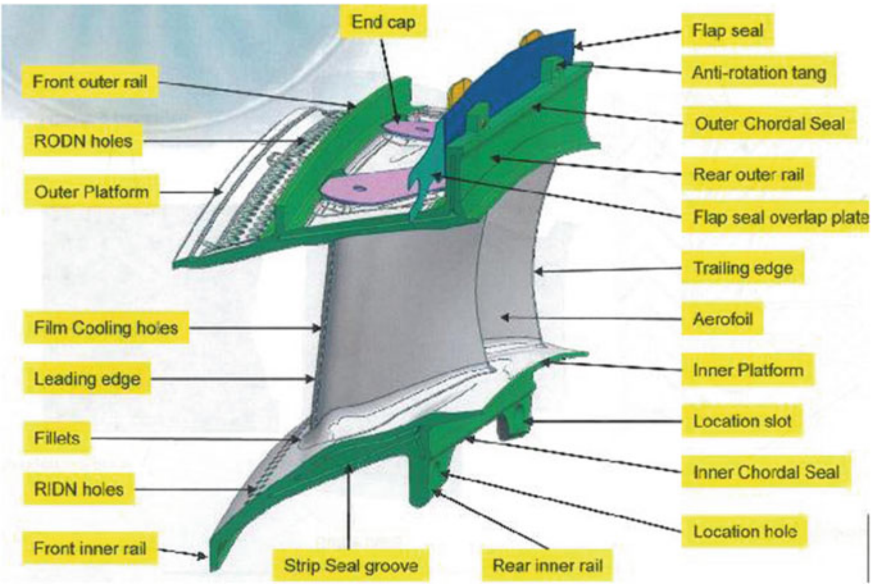

Fig. 1 Typical high pressure Nozzle Guide Vane and Nomenclature (permission granted by copyright holder—2014)

In order to answer the questions proposed and thus achieve the research aim a three stage research programme is presented.

Stage 1: A review of the literature (*Question* 1–3)

Stage 2: To apply IDEF0 and IDEF3 modelling techniques to gain a thorough understanding of the 'AS-IS' condition for the whole life support of the HPNGV supplied by the host manufacturer (*Question* 3)

Stage 3: Presentation of how service knowledge may be used to inform design (*Question* 4)

The next section of the paper will review the literature relative to questions (way marks) posed from which definitions for design knowledge and service knowledge will be offered.

3 The Role of Data, Information and Knowledge in Support of Design: Literature Perspectives

With increasing levels of data being acquired from the aforementioned technical applications the importance of effective data, information, and knowledge management becomes increasingly apparent and the volume of data is becoming incalculable. This has led to a plethora of research initiatives with an emergent focus upon 'Big Data' [29]. The technology, manufacturing, and engineering sectors are no exception to this exponential growth in data generation and acquisition. Data however is just that, data. Of itself it is inert and has little use in its acquired form. It is only when data is reviewed and given context does it acquire value by being information, and ultimately through understanding, it becomes knowledge.

In seeking to understand the distinction between data, information, and knowledge one finds guidance from the literature. Reference [30] states that data is comprised of text and numbers whilst information is the alignment of the data to the context in which it was acquired [30]. Within service delivery systems and product MRO support functions the initial performance and degradation data from service activities and condition monitoring applications can be viewed as data. It is only when the data is aligned to the context from which it is acquired can it be termed information, and only once analysed does this information gain understanding and thus it becomes knowledge. It can be seen that a hierarchy of data, information, and knowledge exists which forms the building blocks for various levels of product support offered by way of a service delivery system. Typically this hierarchy is seen in the fields of Control Engineering, Systems Engineering, and Information and Knowledge Management Systems. It forms the basis of such technical support applications as Condition Based Management (CBM_1) [31], Condition Based Maintenance (CBM_2) [32, 33], and IVHM [34, 35] systems facilitated by the Open-System Architecture–Condition Based Management (OSA–CBM) framework [34, 36].

In consideration of the concepts identified the research questions (way marks) posed in the previous section of this paper emerge.

3.1 What Is Knowledge and How Is It Represented?

Much has been written in the literature relative to the definition, content, context and dimension of knowledge. Most contributions tend to be philosophical in nature rather than focusing on application. The authors have resisted the temptation to just adopt a definition, choosing to illustrate the grounding of the definitions offered in this paper. This section of the paper re-visits elements of the literature (not exhaustive) in order to develop definitions for 'design knowledge' and 'service knowledge'. In seeking to address the questions posed the authors initially sought guidance from the Oxford English Dictionary which defines the concept as:

i. "Facts, information, and skills acquired through experience or education; the theoretical or practical understanding of a subject.

    (a) The sum of what is known: the transmission of knowledge
    (b) Information held on a computer system
    (c) Philosophy, true justified belief; certain understanding as opposed to opinion

ii. Awareness of familiarity gained by experience of a fact or situation" [Oxford English Dictionary]

Knowledge can be either tacit or explicit [30, 37]. Explicit knowledge can be articulated and codified by way of formal language which may be textual, numeric, and/or alpha-numeric [38]. This ability results in the capability to share knowledge content, context, and meaning with other sources without losing its integrity. This for the authors is critical to the process of servitization supported by product/asset condition and degradation knowledge. As manufacturing organisations move from offering base services, through intermediate level service provision, to advanced services offerings and availability contracting [39] supported by monitoring technologies [40] and MRO functions [41, 42], the ability to develop, store, and recall knowledge relative to product usage and performance becomes essential in order to deliver timely service response.

Tacit knowledge is the collection of understanding and experiences which reside within the individual person or entity as a collective. It comprises of two distinct elements. The technical component of such knowledge resides in the practical skills and product/process know-how which is employed in the understanding of tasks but is not codified. The second element of tacit knowledge is cognitive and is evolved from the beliefs and viewpoints of the individual and makes it difficult to codify and disseminate.

Information is defined as the flow of messages (data) which may have syntactic and semantic elements [43]. This is of particular importance when considering Information Retrieval Systems (IRS) which deal with the "searching, retrieving, clustering, and classifying the data, particularly text and other structured forms" [44]. Here such systems offer the semi-structured searching and clustering of text records based upon the classification of data. Reference [44] state that semantic retrieval systems identify and make sense of the data returned based upon the context to which the data refers by identifying the concepts which structure the text. The IRS do this by having 'built in' understanding of the 'ability to learn' syntax (how to say something) and the semantic (the meaning behind the text) [44].

Barons Business Directory defines syntax or (syntactic information) as relating to rules governing the information of statements within a programming language relative to computer science. It therefore facilitates the location, sharing, and combination of datasets thus enabling greater understanding and the derivation of knowledge. It is seen that information is the flow and exchange of data [45, 46] which facilitates the formulation of knowledge through the meaning of the data (message) and the mode and context in which it is acquired [43].

A further categorization of knowledge is that it is either 'Declarative' or 'Procedural' [47]. In the aforementioned categories it is seen that both tacit and explicit knowledge focuses upon the explanation of the concept of knowledge relating to its definition, transformation, dissemination, and application. For Zack [47] an alternative view is that of the application of knowledge. Here, declarative knowledge relates to the content of knowledge (the 'know what'), whilst procedural knowledge relates to the processes required to use the knowledge (the 'know how'). In addition a third element is found which is 'Causal knowledge' (the 'know why') [43]. For Mountney [43] causal knowledge refers "… to the underlying recognition of where it is appropriate to apply … . [the content] … . knowledge" [43]. Finally knowledge can be either, broad and easy to codify and thus disseminate, or specific with results in greater difficulty in codification due to lack of a common synta32 and/or domain.

All of these theories have strengths and weaknesses and the literature has many contributions that attempt to understand the comparisons and interactions to which the reader could refer. For the focus of this paper the authors suggest that each of the aforementioned lenses is equally valid and the choice of theory depends upon the aspect of the study. When seeking to understand the holistic nature and identity of knowledge and its application to industrial cases the research (and reader) should be fully aware of each of these dimensions.

3.2 Design and Service Knowledge and the Product Innovation Process

References [48, 49] propose that the effective use of knowledge is essential to the success of any organisation. Mountney's [43] study on innovative manufacturing knowledge reviews how contributions to the literature relative to knowledge for innovation align with the theories discussed earlier. In observing the interaction of differing types of knowledge Mountney refers to the SECI model for the dynamic theory of knowledge creation (Fig. 2) [46].

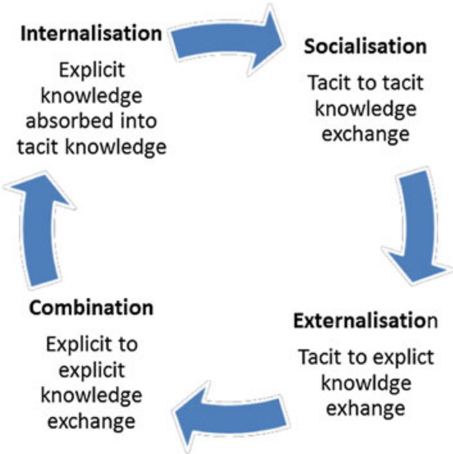

Fig. 2 The SECI model for organisational knowledge creation [45, 46]

The *socialisation* phase represents the knowledge transfer by face to face exchange and the sharing of mutual or collective experience (i.e. the craftsman and his apprentice). This knowledge exchange is difficult to formalise and is context specific. The second phase in organisational learning is the *externalisation* phase. Here tacit knowledge is typically codified and published by way of textual records, drawings and other means of recording, communicating and disseminating learning. When tacit knowledge is codified and made explicit it is crystallised and facilitates the sharing of its contents to third parties enabling new knowledge to be generated. The product design process is an example of this as ideas move through concept, initial design, feasibility analysis, to final design.

Combination is the third phase of knowledge creation. Here differing types of explicit knowledge is combined to yield new solutions and learning. In today's operating companies this is typically facilitated by the use of computer based technologies and digital networks which offer large scale data bases. The advent of cloud computing and the issues of 'Big Data' offer immense opportunities and challenges in the field of organisation learning. Such explicit knowledge is harvested from many sources, processed and then disseminated throughout the host organisation. The final stage in the model is that of *Internalisation.* Explicit knowledge is received by the user and then applied. Quite simply it becomes part of the individual's knowledge and experience and is then ready to be passed on in the next iteration of the model.

Technical (design and service support) knowledge is defined as "the knowledge associated in realising products and services" [50]. For Stokes [51] the requirement to "design and manufacturer for service is … essential … . " and implied within their assertion are the benefits by way of increased service life (availability for use) that can be obtained when service knowledge becomes an input to the design process, thus enhancing design knowledge.

Design knowledge can be classified as having two dimensions, namely

i. product knowledge, and
ii. design process knowledge (Fig. 3) [51].

Product knowledge includes geometric modelling techniques (CAD systems and simulation packages) which can support the detailed design of the product, whilst knowledge modelling (capture and dissemination of what is known) is used when developing designs from concept to detail. In contrast, Design Process Knowledge is also described as existing in two levels

i. design activities, and
ii. design rationale [52].

Typically design activities for a given product are requirement and specification specific, and are represented and guided by coded procedure (explicit/declarative/procedural knowledge) and the experience of the designer (tacit/causal knowledge). The design rationale is informed by the collective body of knowledge and understanding of the collective (stakeholder requirements, standard practice, legislation, standards, knowledge of use, knowledge of failure and degradation, and methods of repair).

When considering design knowledge for any product is also relates to three primary attributes of the product

i. "the physical layout of the product (form)",
ii. "the function of the product and the effect of that function",
iii. "the causal effect of the use of the function of the product (behavior)" [52]

In consideration of these attributes relating to design knowledge the following definition is offered which seeks to cover the full scope of the concept.

> Design knowledge is the summation of understanding relative to product form, function, and the causal effect of a products usage, supported by both explicit and tacit knowledge which can be either declarative or procedural, and an understanding by feature and/or attribute of the modes of manufacture, mechanisms of degradation and failure, and modes of repair.

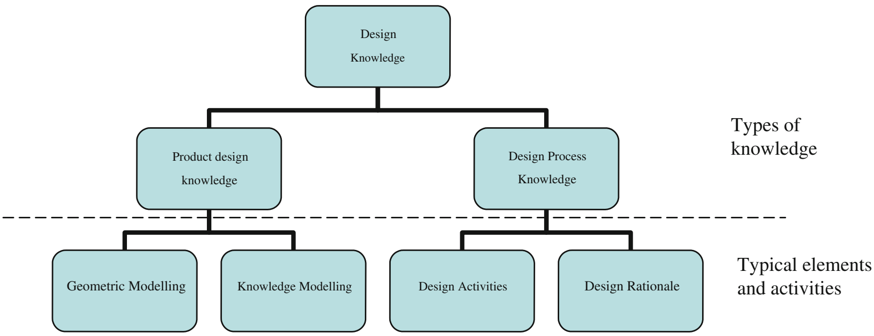

Fig. 3 Elements of design knowledge

The research aim seeks to investigate how service knowledge may be used to inform design. In so doing a definition of service knowledge is required. Again the Oxford Dictionary is consulted to understand what is meant by service within the context of this work. Upon review it is found that 'service' in this context is defined as the act of "… perform[ing] routine maintenance or repair work on a … . [product/asset] …". Clearly to undertake such an undertaking there is a requirement for knowledge and understanding as to the mode of use, mechanism of degradation, cause and effect of such degradation supported by route cause analysis of the failure, supported by knowledge and understanding of the mode of repair. It is important to note that to conduct a service activity is to change the state of the component. This can be either physically (by restoring original condition), or/and improving the operational life (increasing the mean time before failure (MTBF)). In acknowledging these elements of service activities the following definition for service knowledge is offered which is grounded in the literature.

> Service knowledge is the ability to initiate a change of state in a product or asset, facilitated by the awareness of the current condition of that product or asset, its historical usage, and the means of restoring the 'as designed' functionality supported by explicit (codified) and tacit knowledge of the degradation and failure mechanisms of that component.

4 The Requirement for a Formal MRO Knowledge Capture, Storage, and Retrieval System to Inform Design for High Pressure Nozzle Guide Vane

Having offered reviewed the definition for 'knowledge', and offered definitions for 'design knowledge' and 'service knowledge', which are both grounded in the literature the research sought to gain understanding of the state of the art relative to service knowledge informed design. To gain such understanding will ultimately require sector and industry based cross-sectional and longitudinal case studies informed by a pilot study. In order to develop greater understanding of the required content, drivers, and inhibitors of service knowledge informed design, a pilot exploratory case study was carried out with an aerospace OEM manufacturing HPNGVs.

The first stage was to understand the 'AS-IS' condition of the 'through-life' cycle process which included design, manufacture and service support for the chosen part. Following direct observation, semi-structured interviews, informal discussions, and document audit (route and process data sheets) functional and knowledge models were constructed in IDEF0 and IDEF3 formats respectively [52]. A typical section of the IDEF0 model is shown in Fig. 4. Whilst the full details of the IDEF models are not reported within this paper the work highlighted that the 'AS-IS' position relative to service knowledge feedback to design was not integrated by default within the case study organisation.

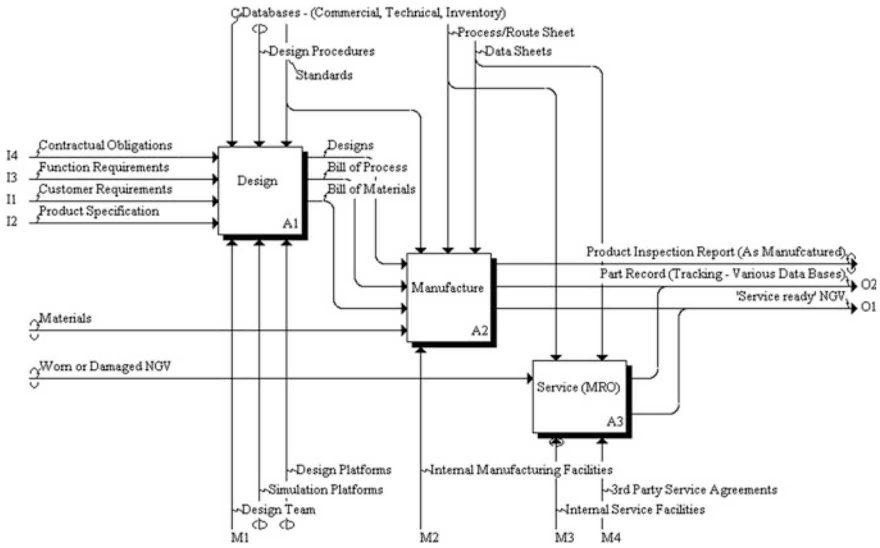

Fig. 4 First level decomposition of IDEF0 diagram for design, manufacture, and service support of HPNGV [52]

Upon examination of the design sections of the models it was observed that the design process is split into three sections

i. concept stage,
ii. preliminary design stage,
iii. full designs accompanied by Bill of Materials (BOM), Bill of Process (BOP) and relevant data sheets.

It is observed that there is significant input from the manufacturing function (example section shown in Fig. 5) into all stages of the design process which takes the form of codified and tacit knowledge with all elements of the design knowledge model (Fig. 3) being easily identifiable. However, the same was not observed when considering the service knowledge feedback into the design of the product. Whilst there is a plethora of evidence to illustrate that service data is being gathered by the MRO functions (Fig. 6), upon discussion with the commodity design team there appeared to be no default position adopted by all, whereby the design process was directly informed by the service data (and subsequent knowledge) as a default definition of the design process (i.e. stage gate control). In contrast to the manufacturing inputs, service inputs (knowledge) were, whilst supported by the engine manuals for the generic engine sets, limited to key performance parameters which were both explicit and tacit in nature.

This observation is supported by the organisation's own internal review findings and formed the justified rationale for the selection of the case study.

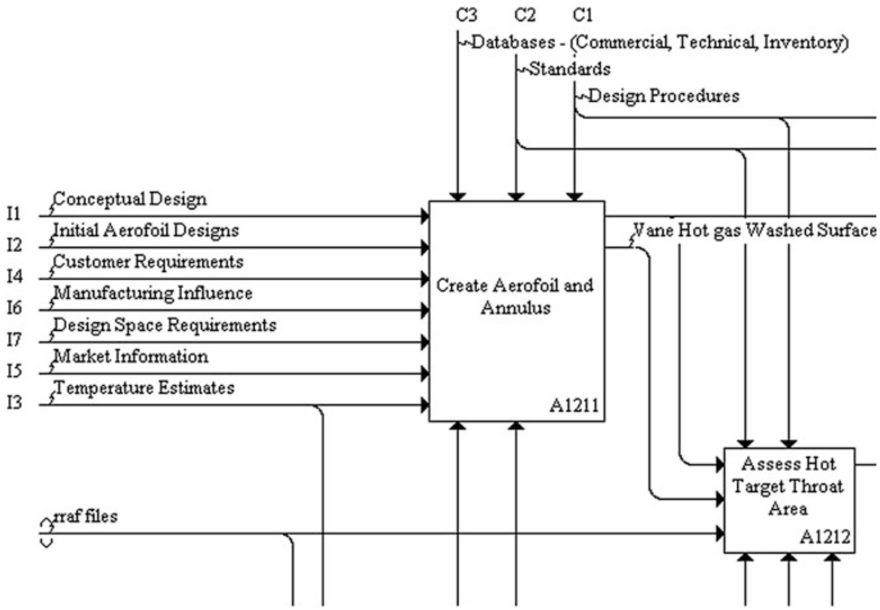

Fig. 5 Partial fourth level decomposition intermediate design stage of IDEF0 diagram for design, manufacture, and service support of HPNGV [52]

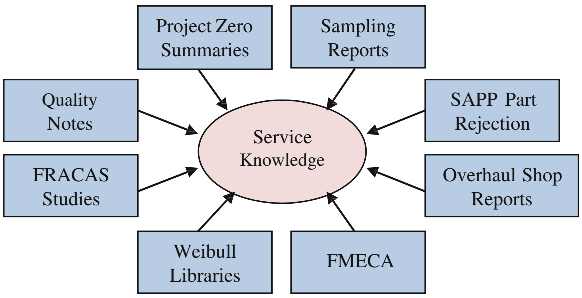

Fig. 6 Types of documented service data available within case organisation (not exhaustive)

5 Discussion

In reviewing the MRO functions for the chosen aero-engine component it is observed that the procedures and systems are well defined and advanced in content and application. The IDEF3 modelling activities illustrate that from component receipt by the MRO facility, through sentencing, repair, and refit, there are much data collected, trended and stored. The authors suggest that this is typical of most OEM's manufacturing complex engineering products. However when seeking to understand the feedback mechanism and content of service acquired knowledge to design developments are not so established or mature.

The typical MRO function within a service delivery system possesses both explicit and tacit knowledge relative to mechanisms of failure, repair technologies and methodologies, and 'lifing' decisions. Upon receipt of HPNGVs the maintenance subjects the component to various dimensional, visual, and non-destructive techniques (typically X-ray and Die Penetrant tests) from which the results (data) are recorded in line with written procedures, standards, and requirements as directed by statutory authorities. Such data is often input into various analytical software tools (e.g. FRACAS) so as to offer trend data (and information) by way of PARETO analysis and WEIBULL data. Whilst these initiates offer information relative to frequency of occurrence and the information (and occasionally knowledge) reported via SAPP and PLM software portals, seldom is the technical and engineering knowledge relating to failure modes and the 'cause and effect' parameters affecting the component's degradation mechanism fed back into the design process by default.

Typically in components of generic design and particularly when produced by a single manufacturer, such components (ref HPNGVs) are the sum of standard features which are imported into the design around common reference planes only to then be connected by defined 'filleting' through the use of 'Non-Uniform Rational B-Spline' (NURBS) applications. In doing this, there is the risk of 'carrying over' design faults and degradation mechanism which exist at the feature level from one engineering issue level to the next. This results in continuing failed components presenting due to 'engineered in' degradation mechanisms which may have been eliminated if only the 'voice' of the service function was given equal consideration to the design process from conceptual stage to issue of final designs.

There are many 'off the shelf' software platforms that can be applied to the problem but they all rely on the correct ontology and taxonomy relative to failure/degradation event/mechanism—the problem of applying the correct and a standard set of definitions, language and syntax throughout the service delivery system. When seeking to establish this all too often does the solution base itself on codified (explicit) standard data. Upon visit to the asset by the service engineer, or presentation of the component to the MRO facility, a standard engineer's report (or component inspection report) is completed which has pre-defined fields for the input. These fields are dependent upon the correct descriptors being identified and entered. Additionally, one often finds a section of the report in which the engineer/inspector is allowed to enter 'free text' into the field describing the failure mode, degradation mechanism, usage data, and or repair process applied or decision to scrap. This is a rich source of data (information and knowledge) which is seldom mined. In the case of an established OEM the amount of data that it holds can be substantial and an inhibitor to analysis. How much better would it be if a system which was self-learning (descriptions, ontologies, etc.) based upon actual inputs from text data which could inform the design process was developed. The final goal of the research programme is the development of such a system. This paper reports the vision and rationale of the undertaking and sets the initial prototype specification for such development (Fig. 7).

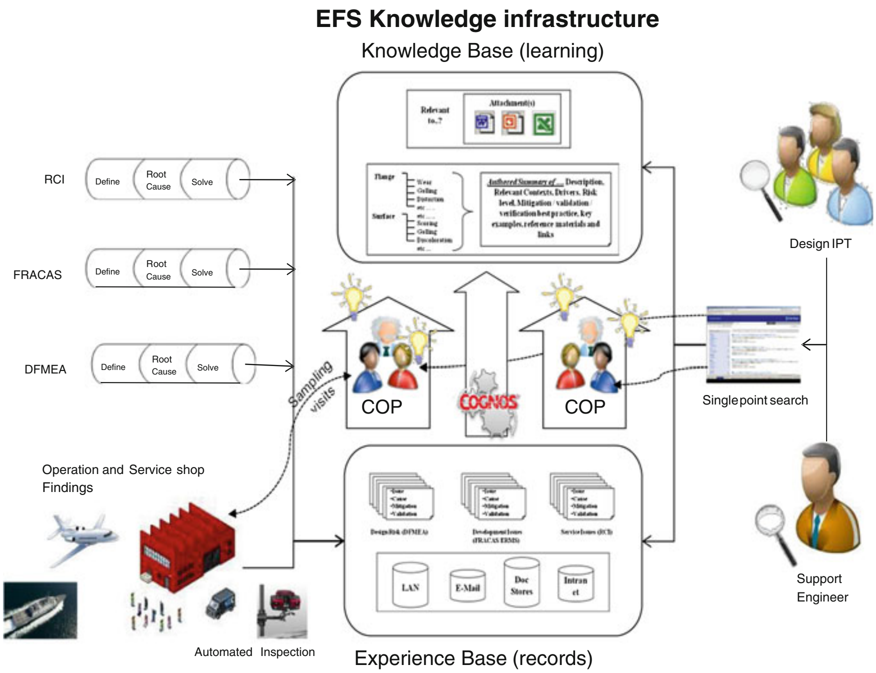

Fig. 7 Proposed design for service (D4S) system architecture (permission granted by copyright holder—2014)

When reviewing the figure it can be seen that as the component arrives at the MRO facility data from inspection, observation, and sentencing activities is acquired. By applying software analytics by way of trending tools (FRACAS, RCI, and DFMEA) information and knowledge becomes available for use by the service support and design functions. Such data and information recording forms both the explicit and tacit knowledge asset base of the organisation and through effective system architectures which enable capture, storage, and easy retrieval by the service and design functions can assist in knowledge based learning. Parallel research is currently being undertaken to develop knowledge based learning by way of 'Term Recognition Software' and supporting algorithms which can collect data from text rich qualitative data contained within service reports, and by 'self-learning' differing descriptors and ontologies for the same degradation mechanisms, offer enhanced knowledge to the overall experience base repository.

The benefit of such a system is clear. The development and application of such a system architecture offers the potential for a single point search for all those who have access to the system. The designer would be able to enter the product he wishes to design (HPNGV) and then the feature (RODN Holes–Fig. 1) and by doing so would be able to get full state-of-the-art knowledge relative to the performance, failure mode, degradation mechanism, and 'life' considerations (cost etc.) when adding the feature to the component design. In the servitized world of the 21st Century where consideration has to be given to global commercial and environmental pressures, the importance of component life and therefore the product's availability for use cannot be overstated.

6 Conclusions

This research seeks to understand, develop, and enhance the role of maintenance, repair and overhaul knowledge in facilitating service led design for gas turbine high pressure nozzle guide vanes. In seeking to define what is meant by service knowledge the research posed several research questions which would act as waymarks towards meeting the research aim. In addressing these questions and after consulting the literature for a definition for 'knowledge', definitions for 'design knowledge', and 'service knowledge' are offered which are grounded in the literature. The research uses this understanding (definitions) and by use of a case study identifies the 'AS-IS' condition relative to the use of service knowledge to inform the design of a selected complex manufactured component for an aero engine. This service knowledge assists in the definition of a system architecture (framework) to deliver for a 'design for service' prototype solution facilitating greater whole-life component availability, reduced costs due to downtime, and potentially lean logistics

This work has formed the exploratory stage of a larger research programme which seeks to develop systems and algorithms which have the ability to apply 'usage' and 'maintenance' knowledge thereby promoting a greater understanding of the characterisation of component feature based degradation mechanisms, and the use of this information to proactively inform the design process. The work has further defined design and service knowledge aligned to the focus of the study. Future research initiatives will include the data-mining of text rich qualitative maintenance data in support of codified explicit service knowledge and through the application of novel analysis and synthesis methods, the knowledge gained will be used to inform an design through a developed integrated system architecture.

Acknowledgment and Funding This research is funded by the Through-life Engineering Services based at Cranfield University which in turn is funded by the UK Engineering and Physical Sciences Research Council

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Identifying the Critical Success Factors for Engineering Asset Management Services—An Empirical Study

J.L. Jooste and P.J. Vlok

Abstract Business-to-business services relating to engineering asset management (EAM) are playing an increasingly important role in industry. This is in the midst of the current pressures which asset owning businesses are experiencing in extracting optimal value from their assets. The pursuit of understanding and complying with asset management standards such as PAS 55 and ISO 55000 contributes towards the importance of these services. This research reports the results of a global study in identifying the critical success factors for collaborating in EAM services. The study identifies the critical success factors; and demonstrates how these factors can differ between role players, industries, global regions and service types. The results reveal that the continued and sustained commitment from the asset owning organization's senior management in support of the EAM services is most critical for a successful EAM service partnership. Open and effective communication is also highlighted as being critical, while it is important to have a process in place to improve the service continuously.

Keywords Engineering asset management services · Partnerships · Engineering asset management collaboration

1 Introduction

Management literature is unanimous in advocating the integration of services into core product offerings. Historically most of the value of a product was added from the production process which transformed raw material to a useful product. Today,

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_32

value comes from technological improvement, styling, branding and other attributes that only services can create [16, 35, 44]. A service is defined as [18]:

> an activity or series of activities of more or less intangible nature that normally, but not necessarily, take place in interactions between the client and service employees and/or physical resources or goods and/or systems of the service provider, which are provided as solutions to customer problems.

Servitization is the term used for offering integrated packages of customer-focused combinations of products, services, support, self-service and knowledge [41]. Although servitization happens in most industries, research has mostly focused on the manufacturing and capital goods sectors [3]. It was found that the services scholarship for other industries is sparse.

Engineering asset management is current. Economic pressures are forcing organizations to increase performance and reduce cost, while managing business risks. This means scrutinizing business processes and investment in assets [40]. Asset owners and operators have adopted the term "asset management" to describe their core business—the combination of investment, exploitation and caring for critical physical assets and infrastructure over their entire life cycle [45].

The Publicly Available Specification, PAS 55, [7] was published in 2004 in response to industry's need for a standard in EAM. PAS 55 includes a specification for the optimized management of physical assets as well as guidelines for applying the specification. Since 2004, PAS 55 has gained acceptance and this has led to the publication of the standard, ISO 55000 [22]. ISO 55000 specifies the requirements for a management system for EAM. ISO 55000 is new and its usefulness to the EAM industry will emerge in the coming years as industry starts working with the standard and becomes familiar with its content. Criticism for PAS 55 is that it provides guidance on "what" to do, but support on "how" to execute the guidelines is insufficient [17, 19, 32]. Similarly, ISO 55000 does not elaborate on specifying processes, methods and best practices to establish the EAM management system.

Although the two standards do not address services explicitly, both include dedicated sections on the requirements for outsourcing EAM activities (paragraph 4.4.2 in PAS 55 and 8.3 in ISO 55000) [7, 32], both of which implicitly refer to the contracting for services.

The increased focus which PAS 55 and ISO 55000 are bringing to the EAM industry, as well as industry and technological changes are leading to more opportunities for professional and operational services in the field of EAM. These changes include, but are not limited to:

- The shift from maintenance management to whole life cycle asset management [2]
- The formalization and industry acceptance of PAS 55 and ISO 55000 as universal EAM standards
- The requirement for industry best practices and processes in support of EAM standards
- The shift from off-the-shelf products to software-as-a-service (SaaS) in the enterprise software industry [11]

- Enterprise Resource Planning (ERP) vendors and service providers expanding their software with computerized maintenance management (CMMS) and enterprise asset management system (EAMS) offerings [20]

It is important for EAM practitioners to be cognizant of the underlying factors that will lead to the success of professional and operational service offerings and partnerships in the EAM arena.

The Critical Success Factor (CSF) approach is appropriate in supporting EAM service synergy. CSFs originate from Information System (IS) literature, which was first published in 1979 [38].

Leidecker and Bruno [26] define critical success factors as:

> those characteristics, conditions or variables that, when properly sustained, maintained, or managed, can have a significant impact on the success of a firm competing in a particular industry.

CSFs have been applied beyond the field of IS to direct strategies, manage projects and guide the execution of activities [4, 12, 13, 29].

2 Research Problem and Design Outline

In the midst of limited best practices in PAS 55 and ISO 55000, the pressure on industry as well as the general lack of scholarship in the area; the problem is that little is known about the underlying factors that guide the success of EAM service offerings and partnerships.

To address the need, this research focuses on identifying the critical success factors which are required for collaborating in a successful EAM service environment, and to determine what the contextual relationships between these factors are.

A mixed method design approach is used for the research. The content of existing literature is analyzed and developed into a Delphi study to identify the success factors relevant to the field of EAM services. The outcomes from the Delphi study are used to develop a survey questionnaire which is used to identify the critical success factors for EAM services. For the questionnaire, data is collected from a sample of EAM service providers and asset owners. The questionnaire outcomes are used to construct a prioritized list of the critical success factors and their contextual relationships for EAM services.

3 Content Analysis

For identifying generic success factors that could be developed further for EAM services, the literature content analysis focuses on fields closely related to EAM. Three fields of study serve this purpose: services, EAM (including maintenance

Table 1 Success factors grouped in six categories supporting to the service life cycle phases

Number	Category	Service life cycle phase
1	Organizational environment and capabilities	–
2	Initiation phase and pre-contract activities	Value proposition phase
3	Preparation and design processes	Systems integration phase
4	Implementation and commissioning	Systems integration phase
5	Control processes	Operational services phase
6	Benefits and value-add	Operational services phase

management) and project management. Project management is of relevance because it forms part of the typology of services—especially more complex service solutions where system and process implementation and integration are required [5, 25].

There has been a steady output of research papers since the 1980s on the identification of CSFs in the aforementioned fields, but not for the synergy between these fields. Some research on CSFs is also found in the fields of outsourcing, information systems and organizational development.

For the literature study a total of 44 papers are identified. Twenty of the papers (45 %) address CSFs in the services field. In eleven of the papers (25 %) CSFs for EAM are covered. These include CSFs for fleet asset management services [33], managing maintenance contractors [34], implementing Total Productive Maintenance [1, 6, 10], maintenance concept development [42] and basic asset care [37]. Eight papers (18 %) cover project management CSFs, two (4 %) identify CSFs in information systems and the remaining three papers (8 %) identify CSFs in other fields (e.g. outsourcing).

Over 550 references to factors are identified and coded from the review of the literature by using the qualitative analysis software, *NVivo* [21]. These coded references are processed by collapsing and combining duplicates. The result is a list of 80 generic success factors that are organized into six categories relating to the service life cycle phases (Table 1) [5].

4 Delphi Study

The Delphi method allows consensus to be reached amongst a panel of experts on a certain issue or topic by using multi-staged questionnaires [24]. For this, research data is collected over multiple rounds by web-based questionnaires. Eighty generic success factors were identified in the content analysis. Panelists rated importance on a 5-point scale, where 1 is *unimportant* and 5 is *very important*. After each round the items which gained consensus are removed. In the next round, the group and individual median and standard deviation statistics are returned with the remaining factors which have not gained consensus. Panelists then have the opportunity to change their ratings considering the statistics. The risk of bias by the researcher in the content analysis phase is mitigated by allowing panelists the opportunity of giving feedback after each round. In round one the panelists have the opportunity to submit additional factors for inclusion in subsequent rounds.

Based on their knowledge and experience in EAM services twenty-five panelists were invited to participate in the research. Nineteen accepted the invitation. There is no clarity as to what the level of consensus for a Delphi study should be. Scholars commonly use levels of consensus ranging between 51 and 100 % [8, 23, 27, 39, 43].

It is unrealistic to use a 100 % level of consensus for this study as the topic being studied is new and will have a degree of unfamiliarity to the panelists. By setting a 100 % level of consensus, there is a risk that none of the factors will gain consensus, and a 51 % level of consensus is likely to be too weak. All of the factors are important in their respective fields. At this level of consensus, the risk is that all of the factors will gain consensus.

A two-thirds level of consensus is set for this study. This is considered to be an appropriate level, since double the number of panelists will agree at this level compared to those who do not agree. Since the panel is homogenous, a 66.7 % consensus is deemed to be a good level to gauge the consensus amongst the group.

After the first round questionnaire 12 of the 80 factors gained consensus. An additional 11 factors were included in round two based on the feedback received from panelists. Following the second and third rounds a further 29 and four factors gained consensus. The Cronbach's α coefficient [28] of the results of the three questionnaires is 0.928, 0.953 and 0.845, all of which are associated with high levels of internal consistency.

The result after the third and final round is that 46 of the 91 generic success factors gained consensus, confirming these factors as important in the context of EAM services and contributing towards the success of these service types.

5 Survey

To determine which of the 46 success factors are the most important—the so-called CSFs—a web-based survey was conducted. The survey questionnaire includes the 46 success factors, which are grouped and numbered according to the six categories in Table 1. The factors for category 1, the organizational environment and capabilities are numbered *1a*, *1b*, etc. For category 2 the factors are numbered *2a*, *2b*, etc. and similarly for categories three through six.

The survey includes 12 strata questions relating to the respondents role in EAM, the industry and economy in which the respondent operates in and the type of assets and services on which the respondents' answers are based (Table 2).

The criticality of the 46 success factors are rated on a 7-point Likert-type scale, with 1 corresponding to *not critical* and 7 corresponding to *extremely critical*. Respondents select any integer level of criticality ranging from 1 to 7.

English and Portuguese versions of the questionnaire were created for data collection.

Table 2 Respondents are asked to relate their rating of the success factors to a specific group of 12 strata questions

Strata	Strata groups
Participant role	Asset owner; service provider
Organizational level	Strategic; tactical; operational
Economy	Developed economies, developing economies
Region	Africa; Asia; Australasia; Europe; North America; South America; more than one of the above regions
Industry	Agriculture; mining; manufacturing; electricity supply; water supply; construction; wholesale and retail trade; transportation and storage; information and communication; finance and insurance; real estate; professional, scientific and technical activities; public administration and defence; education; health care; arts, entertainment and recreation; more than one of the above; other
Sector	Private; public; non-profit
Asset life cycle	Needs identification; feasibility studies and/or planning; specification and design; acquisition, installation and commissioning; operation and maintenance; decommissioning and disposal; more than one of the above
Asset type	Mechanical or electro-mechanical equipment or machinery; facilities; infrastructure and linear assets; other
Service type	Basic asset-orientated services; professional support services; outsourcing services; integrated life cycle services
Service timespan	Short term; short to medium term; medium term service contract; long term service contract
EAM maturity	Low; low-medium; medium; medium-high; high
Service size (number of people involved)	1–5; 6–15; 16–30; 31–100; >100

A combination of sampling strategies is used. For a selection of the most active EAM *LinkedIn* groups, group members were invited to participate in the survey by posting an invitation on the group discussion boards. A US based EAM media company published the survey twice as a promotion in their weekly newsletter and invited its members to participate in the study. Members of the EAM associations in South Africa and Brazil were also invited to participate and two South African EAM and a Brazilian service provider distributed a request for participation to their consultants and client distribution lists. In addition prominent EAM practitioners were personally invited to participate via email.

5.1 Results

A total of 392 responses were received of which 254 were valid (all questions were answered). Figure 1 shows four of the response distributions. The ratio between

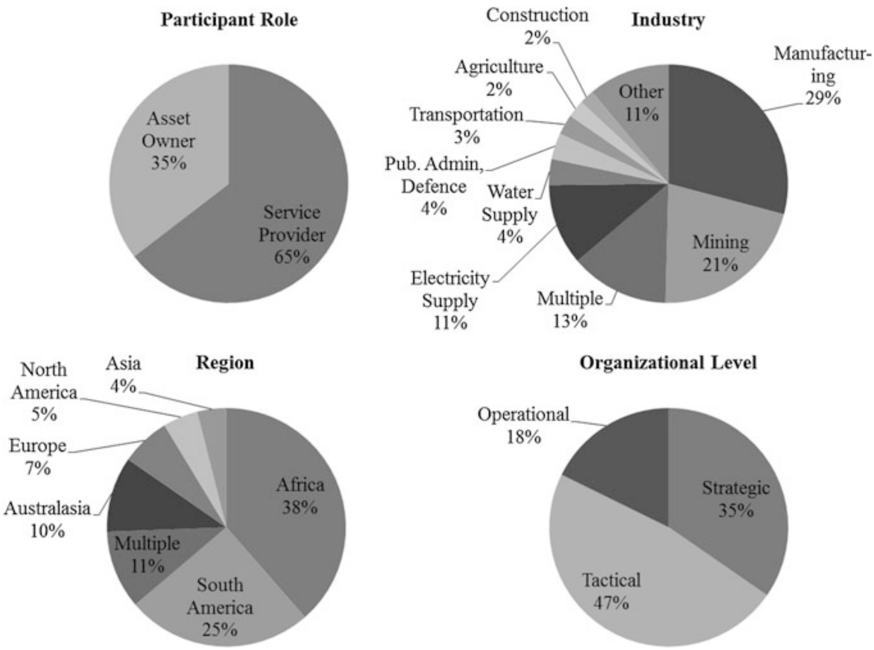

Fig. 1 Characteristics of the sample distribution for the participant's role in the EAM service, the organizational level, region and industry of operation

asset owner and service provider responses is 1:2. Of the respondents 82 % work in a strategic or tactical capacity. The majority of the responses originate from Africa (38 %) and South America (25 %). A further 11 % of respondents indicated that they work globally in EAM services and 10 % in Australasia. The remaining 16 % originate from Europe, North America and Asia. Respondents operating in the manufacturing industry represent 29 % of the responses, while 21 % of the responses come from the mining industry. Respondents working in multiple industries represent 13 %, and a further 11 % is attributed to responses from the electricity supply industry.

The use of parametric statistics (i.e. mean scores, normality, analysis of variance) for analyzing Likert-type data have been ratified as being acceptable. Scholars reason that these response formats have an underlying continuum for which parametric statistics produce fairly accurate results, and concerns about treating ordinal data as interval data in the process are unfounded [9, 14, 15, 31]. Parametric statistics are used to analyze the results and a sensitivity analysis of the correlations between the parametric and non-parametric rank measures the deviations.

Table 3 shows the descriptive statistics of the results. Overall the central tendency of the success factors ratings is closer to the upper limit of 7 representing *extremely critical*. The means for the 46 factors range between a minimum of 5.118 and maximum of 6.413, while both the medians and modes range between 5 and 7.

Table 3 Descriptive statistic of the success factors from the survey results

Factor	N	Mean	Lower 95 % CI	Upper 95 % CI	Med	Mode	Freq. of mode	Min	Max	Std. dev	Std. err	Rank (Mean)
1a	254	5.953	5.817	6.089	6	7	97	1	7	1.099	0.069	19
1b	254	5.720	5.583	5.858	6	6	87	1	7	1.109	0.070	32
1c	254	5.969	5.852	6.085	6	6	104	2	7	0.945	0.059	16
1d	254	5.870	5.754	5.987	6	6	106	3	7	0.942	0.059	23
1e	254	5.831	5.701	5.960	6	Mult	81	2	7	1.048	0.066	27
1f	254	6.110	5.989	6.231	6	7	110	3	7	0.980	0.061	10
2a	254	6.413	6.303	6.524	7	7	158	2	7	0.897	0.056	1
2b	254	5.965	5.831	6.098	6	7	93	1	7	1.083	0.068	17
2c	254	6.150	6.033	6.266	6	7	108	2	7	0.946	0.059	5
2d	254	5.276	5.114	5.437	5	5	74	1	7	1.308	0.082	40
2e	254	5.827	5.686	5.967	6	7	86	1	7	1.136	0.071	28
2f	254	5.980	5.854	6.106	6	Mult	92	2	7	1.019	0.064	15
2g	254	5.752	5.622	5.882	6	6	91	2	7	1.055	0.066	31
3a	254	5.713	5.584	5.842	6	6	98	3	7	1.045	0.066	33
3b	254	5.776	5.650	5.901	6	6	86	3	7	1.018	0.064	30
3c	254	5.260	5.112	5.407	5	5	85	2	7	1.194	0.075	42
3d	254	5.268	5.118	5.417	5	6	76	1	7	1.209	0.076	41
3e	254	5.193	5.027	5.358	5	5	76	1	7	1.339	0.084	44
3f	254	5.524	5.379	5.668	6	5	80	2	7	1.172	0.074	36
3g	254	5.142	4.989	5.294	5	5	80	1	7	1.233	0.077	45
3h	254	5.791	5.636	5.947	6	7	91	1	7	1.257	0.079	29
3i	254	5.500	5.332	5.668	6	7	71	1	7	1.362	0.085	38
3j	254	5.858	5.731	5.985	6	6	98	2	7	1.027	0.064	25

(continued)

Table 3 (continued)

Factor	N	Mean	Lower 95 % CI	Upper 95 % CI	Med	Mode	Freq. of mode	Min	Max	Std. dev	Std. err	Rank (Mean)
3k	254	5.402	5.251	5.552	5	5	81	1	7	1.218	0.076	39
3l	254	5.228	5.049	5.408	5	6	66	1	7	1.451	0.091	43
3m	254	5.862	5.739	5.985	6	6	109	2	7	0.994	0.062	24
3n	254	6.087	5.968	6.205	6	7	102	2	7	0.958	0.060	11
4a	254	6.134	6.022	6.246	6	7	106	3	7	0.906	0.057	7
4b	254	6.134	6.009	6.259	6	7	107	1	7	1.013	0.064	7
5a	254	5.839	5.718	5.960	6	6	97	3	7	0.979	0.061	26
5b	254	5.504	5.376	5.631	5	5	87	2	7	1.032	0.065	37
5c	254	5.957	5.834	6.079	6	6	91	1	7	0.991	0.062	18
5d	254	5.984	5.863	6.105	6	7	96	3	7	0.978	0.061	14
5e	254	5.118	4.953	5.283	5	5	81	1	7	1.337	0.084	46
5f	254	6.323	6.216	6.429	7	7	130	1	7	0.861	0.054	2
5g	254	6.157	6.034	6.281	6	7	118	2	7	0.997	0.063	4
5h	254	6.067	5.949	6.185	6	6	99	2	7	0.953	0.060	12
5i	254	5.878	5.757	5.999	6	6	108	2	7	0.980	0.062	22
5j	254	6.118	6.005	6.231	6	7	104	3	7	0.912	0.057	9
5k	254	5.921	5.806	6.037	6	6	113	2	7	0.933	0.059	20
6a	254	5.673	5.538	5.808	6	6	99	1	7	1.092	0.069	34
6b	254	5.902	5.779	6.025	6	6	101	2	7	0.995	0.062	21
6c	254	5.646	5.503	5.788	6	6	92	1	7	1.153	0.072	35
6d	254	6.122	5.998	6.246	6	7	112	2	7	1.000	0.063	8
6e	254	6.059	5.943	6.175	6	6	103	3	7	0.937	0.059	13
6f	254	6.181	6.072	6.290	6	7	112	3	7	0.884	0.055	3

The factors show minimums of 1, 2 and 3 and all show a maximum of 7. The standard deviation, which is a measure of variation from the mean, varies between 0.861 and 1.451.

The standard error is the standard deviation of the sample mean's estimate of the population mean. Standard errors for the factors vary between 0.054 and 0.091. The last column in Table 3 indicates the rank of each factor based on the value of the mean. It is seen that factor *2a* and *5f* have the highest means of 6.413 and 6.323 respectively. In addition, factors *1f*, *2c*, *3n*, *4a*, *4b*, *5g*, *5h*, *5j*, *6d*, *6e* and *6f* all have means above 6. The remaining 33 factors' means fall in the band 5–6.

Table 4 shows the ranked CSFs based on means, for mean values above a criticality benchmark of 6.

Table 5 presents the results of the sensitivity analysis for the correlations between the mean ranks, the ranks of the median (non-parametric) and four other measures commonly used to analyze questionnaire data. The definitions of the measures are:

Table 4 Prioritized list of CSFs based on mean ranking

CSF	Mean	Description
2a	6.413	The continued and sustained commitment from the asset owner senior management in support of the EAM service
5f	6.323	Open and effective communication between the asset owner and service provider
6f	6.181	A focused and continuous improvement process to improve the EAM service through monitoring, analysis and feedback
5g	6.157	Mutual trust and respect between the service provider and asset owner
2c	6.150	The alignment of the asset owner's EAM service requirements with their overall organizational and business strategies
4a	6.134	An adequate training program in place for all EAM service role players, both in the service provider and asset owner teams
4b	6.134	An effective organizational change management program in support of the EAM service
6d	6.122	Proof of operational and financial performance achievements as a result of the EAM service
5f	6.323	The use of a performance measurement system to monitor, control and improve the EAM service
1f	6.110	The integrity of the leadership and delivery team and the set of values to ensure sustainability of the service
3n	6.087	The involvement of knowledgeable and demanding individuals from the client during the design and preparation, rather than individuals who want to abdicate their EAM responsibilities
5h	6.067	Active client participation in reporting, problem solving and improvement relating to the EAM service
6e	6.059	The ability to measure the EAM service quality and value creation

Table 5 Rank correlations between parametric and non-parametric statistics

	Means	Std. dev	Mean	Median	Top box	Top two box	Net top box	Percentile rank
Mean	23.500	13.422	1.000	0.739	0.957	0.982	0.963	0.998
Median	23.500	9.974	0.739	1.000	0.743	0.744	0.743	0.743
Top box	23.500	13.416	0.957	0.743	1.000	0.935	0.998	0.958
Top two box	23.500	13.415	0.982	0.744	0.935	1.000	0.939	0.980
Net top box	23.500	13.416	0.963	0.743	0.998	0.939	1.000	0.963
Percentile rank	23.500	13.423	0.998	0.743	0.958	0.980	0.963	1.000

- Top box: The percentage of respondents who rated a success factor as 7 on the scale.
- Top two box: The percentage of respondents who rated a success factor 6 or 7 on the scale.
- Net top box: The difference between the total number of top responses (7 s) and the number of bottom responses (1 s) expressed as a percentage of the total responses.
- Percentile rank: A six sigma technique converting the raw score to a normal score and expressing it as a percentile rank. The z-value is calculated by comparing the success factor mean to a reasonable benchmark. A benchmark of 5.807—the mean of all the collected data—is used [30].

It is evident that the alternative ranks are closely correlated with the mean ranks, which shows no evidence of adversities for applying parametric statistics to the data.

5.2 Analysis of Variance (ANOVA) of Strata

In light of the prioritized list of CSFs, it is of interest to investigate whether there are different perspectives about the CSFs for the different response groups of the 12 strata. Analysis of variance is performed to investigate the effect of each stratum independently in the context of the success factors. A multivariate test of significance is done to account for all success factor relationships within each stratum. Table 6 shows the *Wilks' Lambda* multivariate ANOVA results for the 12 strata [14].

Three of the 12 strata show significant differences at a level of significance of 0.05. The remaining nine strata show no significant differences, which indicates there is no significant difference between the means of the different response groups within each stratum.

Univariate ANOVA is calculated for the participant role, organizational level and region. Table 7 summarizes the success factors with significant differences between the response groups' means at a level of significance of 0.05. The results show few significant differences in the top ranked items—CSFs with means of six

Table 6 Wilks' Lambda multivariate test for the 12 strata ($p < 0.05$ indicated by*)

	Wilks' Lambda multivariate tests of significance marked differences are significant at p < 0.05				
Stratum effect	Value	F	Effect df	Error df	p
Participant role					
Intercept	0.006	774.122	46	207	0
Role	0.721	1.744	46	207	0.005*
Organizational level					
Intercept	0.006	740.082	46	206	0
Level	0.564	1.487	92	412	0.005*
Economy					
Intercept	0.006	734.326	46	207	0
Economy	0.828	0.935	46	207	0.596
Region					
Intercept	0.009	481.329	46	202	0
Region	0.213	1.303	276	1212	0.002*
Industry					
Intercept	0.019	211.705	46	191	0
Industry	0.034	0.943	782	3138	0.848
Sector					
Intercept	0.073	57.239	46	206	0
Sector	0.617	1.225	92	412	0.096
Asset life cycle					
Intercept	0.023	186.260	46	204	0
Life cycle	0.413	1.100	184	817	0.196
Asset type					
Intercept	0.013	346.221	46	205	0
Asset type	0.560	0.952	138	615	0.633
Service type					
Intercept	0.006	716.583	46	205	0
Service type	0.561	0.948	138	615	0.644
Service timespan					
Intercept	0.008	535.911	46	205	0
Timespan	0.572	0.914	138	615	0.739
EAM maturity					
Intercept	0.008	554.283	46	204	0
EAM maturity	0.407	1.123	184	817	0.150
Service size					
Intercept	0.006	798.014	46	204	0
Size	0.501	0.840	184	817	0.928

Table 7 Success factors with significant differences between means ($p < 0.05$ indicated by *) according the univariate ANOVA results

		Strata					Strata		
Factor	Mean	Role	Org. level	Region	Factor	Mean	Role	Org. level	Region
2a	6.413				3m	5.862			
5f	6.323				3j	5.858		*	
6f	6.181		*	*	5a	5.839	*	*	*
5g	6.157				1e	5.831		*	
2c	6.150				2e	5.827	*	*	*
4b	6.134		*		3h	5.791	*	*	*
4a	6.134				3b	5.776			
6d	6.122				2g	5.752		*	*
5j	6.118				1b	5.720		*	*
1f	6.110				3a	5.713		*	
3n	6.087				6a	5.673			
5h	6.067		*		6c	5.646		*	*
6e	6.059		*		3f	5.524		*	
5d	5.984	*	*		5b	5.504		*	*
2f	5.980				3i	5.500		*	*
1c	5.969		*	*	3k	5.402		*	*
2b	5.965		*		2d	5.276		*	*
5c	5.957				3d	5.268		*	*
1a	5.953	*			3c	5.260		*	*
5k	5.921		*	*	3l	5.228		*	*
6b	5.902			*	3e	5.193		*	*
5i	5.878		*	*	3g	5.142		*	*
1d	5.870			*	5e	5.118			*

and above. This indicates that the majority of respondents agree on the top CSFs without any evidence that there are adversely different perspectives on these CSFs.

To determine which of the strata response groups are responsible for the significant differences, Tukey-Kramer post hoc tests are performed [36]. The post hoc test for the participant role stratum shows significant differences for success factors *1a*, *5a* and *5d*, but not for *2e* and *3h*. Service providers value a capable project manager (*1a*) and the active management of the service relationship (*5d*) significantly higher than the asset owner. In contrast, the asset owner is significantly more concerned with the close monitoring of budgets and costs of the EAM service (*5d*).

The post hoc tests for the organizational level reveal 19 of the 29 success factors show significant differences between the response group means. Table 8 summarizes the differences between strategic, tactical and operational groups' responses, for the 19 factors. For all of the factors in Table 7 the operational group means are significantly higher than the comparative group means.

None of the significant differences between the means are attributed to differences between tactical and strategic participant perspectives. Operational

Table 8 A summary of the Tukey-Kramer post hoc test results for the organizational level stratum

Response groups with significant differences between means		Affected factors
Operational	Strategic and tactical	*2d, 2e, 3c, 3d, 3g, 3h, 3l, 5b, 5e, 6c, 6f*
Operational	Tactical	*2g, 3e, 3j, 3k, 5i, 5k, 6e*
Operational	Strategic	*3i*

Table 9 A summary of the Tukey-Kramer post hoc test results for the regional stratum

Response groups with significant differences between means		Affected factors
South America	Australasia	*2e*, *3d*, *3e*, *3i*
South America	Europe	*3g*, *5i*
South America	Africa	*5e*
South America	Multiple regions	*5b*
South America	Africa and multiple regions	*3h*
South America	Australasia and Europe	*1b*
South America	Australasia, Europe and multiple regions	*3k*
South America	Africa, Australasia, Europe and multiple regions	*3l*

respondent views differ significantly from both strategic and tactical perspectives for 11 of the factors. Seven factors show significant differences between operational and tactical perspectives and one between operational and strategic perspectives.

The post hoc tests for the regions reveal 12 of the 22 success factors show significant differences for the response group means of the different regions (Table 9). For all the factors the South America group means are significantly higher than the comparative group means.

It is seen that South America is the common denominator for all significant differences among success factors in the region stratum. None of the factors show significant differences between any combinations of the other six regions. For all the factors in Table 9 the South America group means are significantly higher than the comparative group means.

Of interest is factor *6f*. It is ranked as the third CSF and the ANOVA results show significant difference for the relationships of the combined regional groups. The Tukey-Kramer post hoc is however inconclusive, with none of the pairwise group comparisons showing significant differences.

6 Conclusion

This is the first study which explores the factors affecting the synergy between EAM and services. It contributes to the EAM body of knowledge by supporting the outsourcing requirements, as stated in PAS 55 and ISO 55000, with essential critical success factors which should be managed for a value-adding EAM service relationship.

A prioritized list of 13 CSFs is presented. These factors should be actively managed by all of the role players for the best probability for a successful EAM service partnership.

There are four underlying themes that emerge from the prioritized list of CSFs. Firstly, there needs to be continuous support from the asset owner management for the EAM service (*2a*, *3n*, *5h*). Secondly the service needs to be built on sustainable collaboration between the asset owner and service provider (2c, *4a*, *4b*, *5f*, *5g*). Thirdly, a performance management system needs to be in place. Such a system should cover: a measurement system and process (*5f*), the proof of operational and financial benefits as a result of the EAM service (*6d*) and the measuring of the service quality and value-add (including, but not limited to operational or financially orientated benefits) (*6e*). Fourthly, the improvement of both the service relationship and the value creation as a result of the service need to be actively managed (*6f*, *5f*).

Asset owners and service providers unanimously agree on the prioritized CSFs. Operational role players in EAM services regard four of the CSFs (*6f*, *4b*, *5h* and *6e*) significantly more important than their strategic and tactical counterparts. It is inconclusive which of the regional groups differ significantly on CSF *6f*. Most of the significant differences between strata response groups are due to differences within the lowermost 60 % of the ranked success factors.

The findings presented in this paper are part of ongoing doctoral research. Based on the reported data, a decision support model is being developed as a contribution to industry. In such a model the survey results would serve as industry benchmarking data. The model would allow for the assessment of a specific EAM service against the CSFs (from the survey results), which should be in place for such a service. This would be done through a structured approach whereby asset owners and service providers would self-assess the service which they are involved in. The model would allow for evaluating alternative CSF priorities for the current conditions or the life cycle phase of the service. Prioritization would be based on weighting the industry benchmark score, the service compliance to the factor, and the level of consensus between the asset owner and service provider regarding the service compliance.

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Risk-Based Approach to Maintenance Management Applied on Power Transformers

R.P.Y. Mehairajan, M. van Hattem, D. Djairam and J.J. Smit

Abstract The power network utility sector is facing immense changes in their operation and management activities due to the deregulation of the market structure. Therefore, asset management (AM) is seen as an essential method to ensure control, gain knowledge and improve decision-making while these changes occur. Risk management is seen as a mainstream regime to enable AM to fulfil the mentioned drivers, because *risk* provides an analytical dimension with the characteristics of being comparable, measurable and manageable. Maintenance management is an essential part within AM, as it forms the means to track and ensure measurable asset performance throughout the asset lifecycle. In this contribution, we introduce risk incorporated *Reliability Centered Maintenance* (RCM) method based on the overall corporate risk management principles. In the developed method, the traditional *Risk Priority Number* (RPN) approach used in RCM studies has been expanded in order to deal with the consequences of asset failure modes on multiple corporate business values.

Keywords Asset maintenance · Risk management · Electrical power transformer

1 Introduction

Immense challenges are posed to power transmission and distribution network utilities as a result of the restructuring and deregulation of this sector. Traditionally, prior to the restructuring and deregulation, network utilities were shielded from challenges because of their status as a natural monopoly. This led to network utilities developing strategies which were not always optimal. Amongst other, such

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_33

strategies could be e.g. "solely technically optimal assessed expansion of networks", "enhancing reliability with all available budgets", "corrective and preventive maintenance strategies which were not based on operational experience or knowledge of dominating failure modes, but on manufacturers specifications or gut feelings". However, after the restructuring and deregulation, network utilities could no longer justify solely technical considered development strategies. More than ever, utilities are required, by regulators, to consider mixed strategies matching technical, economic and social requirements in their investment decisions [1]. Hence, a paradigm shift took place in the business perception of traditional network utilities from technical managed systems to socio-technical managed systems [2]. In this context, AM (with risk management as mainstream regime) is seen as a socio-technical system and is being adopted by many asset intensive industries worldwide [3]. Consequently, this will also have important implications for maintenance management, which forms an essential part of AM. Maintenance management strategies have developed in the last decades from corrective into predictive and risk based. In the power sector, a mix of maintenance strategies (corrective and preventive) and policies (time based, condition based, reliability centered and risk based) is in use and will continue, albeit in different proportions, for the future. In general, the evolvement involves a paradigm shift from a solely reactive strategy through preventive strategies to, finally, predictive strategies (mix of policies). In Fig. 1, the main characteristics of maintenance strategies (corrective and preventive) and two policies (reliability centered and risk based) are given.

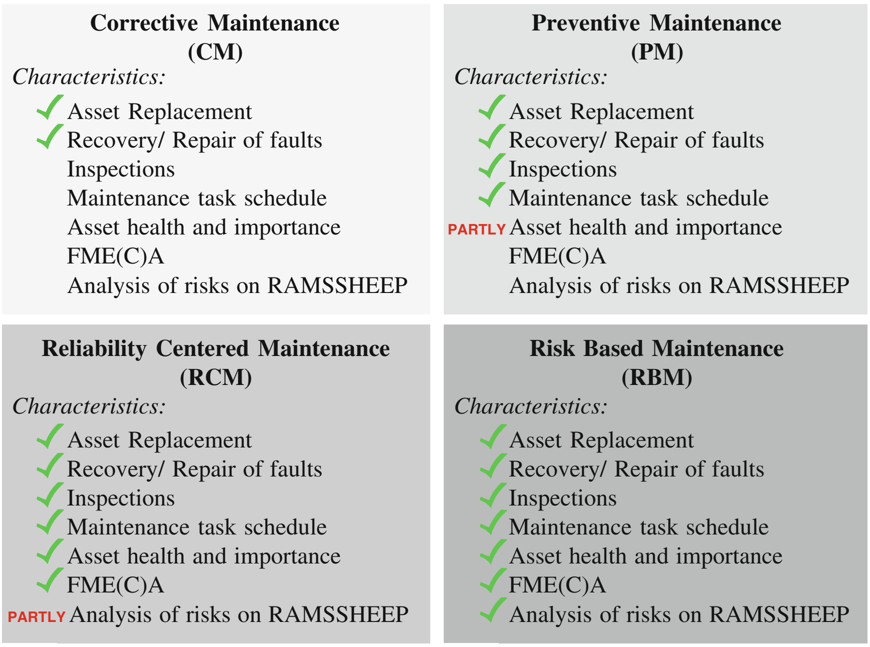


Fig. 1 Mainstream maintenance developments and a number of their important characteristics

Similar sector and maintenance developments, as previously described, have led Stedin BV, the third largest Dutch electricity and gas distribution network operator (DNO), to adopt an AM approach which has led to successful PAS55 certification since 2008. This approach aims to continuously optimize the management of assets throughout their lifecycle in order to deliver value and achieve the organisation's purposes.

In this contribution, we will expand on different aspects of maintenance management capabilities. The main focus is on the development of a risk management approach for the application of *Reliability Centered Maintenance* (RCM) as part of an advanced policy for maintenance management. We witness that the maintenance development for power network utilities will have a mix of strategies in which advanced utilities will be driven by risk-based policies, but tempered with the practicalities and economics of planning maintenance and maximising asset availability. This will enable deliberately considered risk mitigating and risk accepting actions in which operational expenses (OPEX) can be proactively managed and scheduled.

This article is organized as follows: in Sect. 2, we will start with describing the importance of taking an integrated organisation approach when professionalising maintenance management. It continues with the application of a maturity model for maintenance which is used to clarify whether, currently, the maintenance organisations process are adequate and what the prospects are for future development. This section closes with a conceptual overview of an advanced maintenance organisation decision-making process for a typical triple-layer AM model. In Sect. 3, we describe risk management and RCM in general in order to further explain the development of our risk incorporated RCM model in more detail, which is an advanced modelled practical method. In Sect. 4, we describe in what way such comprehensive methods should be combined with the overall decision-making process.

2 Organization—Wide Approach for Maintenance Management

2.1 Maintenance Management Supporting Pillars

According to [4], maintenance is defined as "the combination of all technical, administrative and managerial actions during the lifecycle of an item intended to retain it in, or restore it to a state by which it can perform the required function". In the same vein, maintenance management is defined as "all the activities of management that determine the maintenance objectives or priorities, strategies and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, and several improving methods including economical aspects". Nowadays, maintenance and maintenance management are considered as a sophisticated field involving operations, human resources, tactical and strategic analytical methods supporting economics, safety and environmental management, etc. [5]. Currently, in many network utilities, maintenance is often a department or function located in the final process of the main supply chain [5]. Due to this, it often happens that maintenance makes assumptions about its specific missions and, on top of that, might improve existing deviations in other departments' missions to meet overall corporate process goals. To tackle this, an organization-wide approach for maintenance improvement has been established. With such an approach, an integrated maintenance management framework to improve all maintenance decisions-making processes has been developed. In this framework, the network utility is able to take into account a myriad of considerations, such as policies, criteria's, information requirements, data systems, techniques and tools to analyse and assess certain maintenance tasks [6]. An integrated approach, rather than a conventional "silos" approach, provides means to incorporate all relevant supporting pillars for maintenance improvement. In our previous research [6] such an organisation-wide approach was developed and will be briefly described here.

As shown in Fig. 2, each necessary maintenance management supporting pillar (column) is linked to a specific asset group (row) (which, for instance, are power transformers, power cables, substations, etc.). For each asset group, a dedicated responsible person is assigned who will map the corresponding maintenance activities to the different organisational maintenance supporting pillars. Based on this, the possible "gaps" between current and future maintenance strategies can be assessed [6]. The future maintenance strategies are assessed in the last column (vision and pilot) of which this article is a result. Detailed description of the supporting pillars for maintenance management can be found in [6].

2.2 Maintenance Management Maturity Model

Although such an approach seems straightforward, it is still a recently adopted approach in practice for the electricity network sector. Historically, electricity network companies would consider maintenance as a merely technical function. Nowadays, maintenance is progressively seen from a holistic business point of

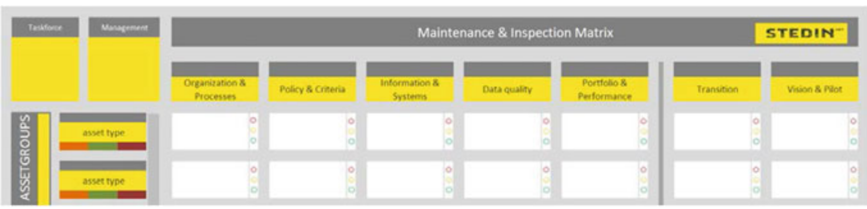


Fig. 2 Illustration of an integrated (organization-wide) style approach which is used as a guidance to take into account all considerations to improve maintenance decision-making processes [6]

view. Many difficulties arise because of the mix-up between different specialities, systems and cultures. Consequently, it is necessary to have the ability to clarify whether the maintenance management process is adequate. In practice this issue often remains unresolved yet it can actually be assessed by means of a maturity model. On one hand, the maturity model serves as an indicator of the current circumstances for each organisation's supporting pillar (Fig. 1). On the other hand, it will form the basis to compare the maturity for different asset groups with each other and is fundamental to develop a mix of maintenance strategies depending on risks associated with the asset groups. The level of maturity is determined by filling out a questionnaire, consisting of 50 questions about all aspects of each supporting pillar. This maturity model is described in more detail in [6]. In Fig. 3, we have illustrated the main characteristics for each maturity level and how that translates to the actions that are taken by the utility. Basically, we recognize the evolvement here, from a restorative regime (occurring risks are vigorously acted on), to a restore and prevent regime (risks are known and managed) and finally an advanced restore, prevent and predict regime (risks are related to lifecycle but tempered with the practicalities and economics of planning maintenance and maximising asset availability). In the remainder of this article, our focus is mainly on the development of a maintenance analysis method that best suits the "best in class" maturity level.

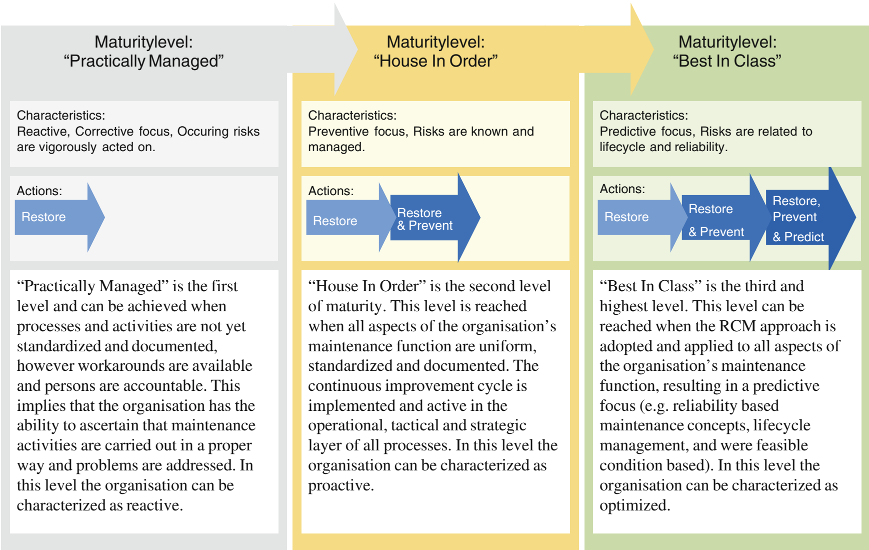


Fig. 3 Brief explanation of the three maturity levels to assess the maintenance management organisation together with the characteristics of each level and which type of actions the utility can be related to

2.3 Risk Management as Guiding Principle for Maintenance Management

Here, we will put maintenance management in the overall context of AM in order to explain how we believe, as well as an international trend, that risk management will form the guiding principle for maintenance management decision-making process [7, 8]. Maintenance management does not only interrelate to operational levels of AM, but no doubt also with other strategic and tactical levels. For this purpose, we have modelled, as shown in Fig. 4, the fundamental steps for a risk oriented maintenance decision-making process.

In a typical triple-level AM model (operational, tactical and strategic) maintenance management information, or decision-making, interrelates with many entities. Firstly, on operational level, inspections, maintenance, construction and component level failures information are collected and reported by service providers to the asset owners departments. Often, these are asset management departments responsible for

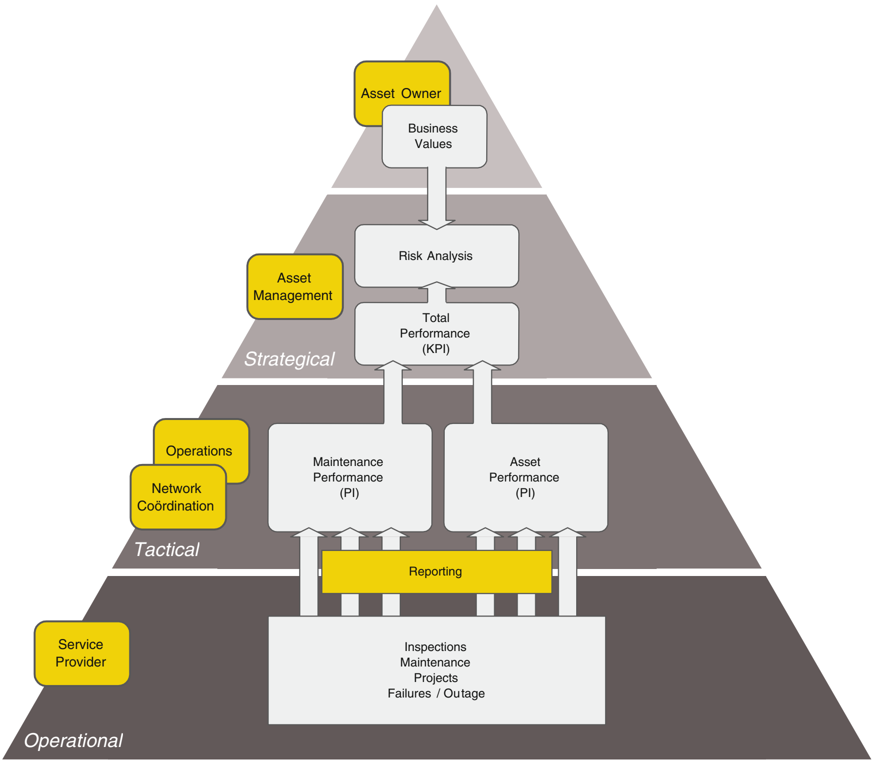


Fig. 4 Risk oriented maintenance decision-making process showing the information flow (*grey arrows*) with the operational, tactical and strategic entities of AM. The *yellow blocks* indicate related responsibilities

the short-term decisions-making on component level. Secondly, the received information is stored in various database systems and can be used for tracking specific maintenance performance indicators (PI) for larger populations (e.g. a group of assets of a similar type). This takes place at tactical level, responsible for mid-term decision-making. Thirdly, on the strategic AM level, key performance indicators (KPI's) are applied to manage complete populations of assets. These KPI's are in accordance to the corporate AM policy. Finally, since maintenance decision-making is risk-based, the decisions are evaluated against the business values.

It should be noted that Fig. 4 is a state of the art process not yet fully adopted in practice, however gradually gaining traction, especially on strategic and tactical level. Also, global interest in having a set of coordinated activities and processes (e.g. for maintenance management) is increasing more and more [7, 9]. Risk management, to which a separate section is devoted in PAS55, gets even more attention in ISO 55000 with emphasis on risk evaluation and control. It is expected that risk management will become more accessible and applicable for operational activities, such as maintenance management. This provides a major opportunity to ensure that the technical aspects of maintenance management form a part of the organizations' AM policy and strategy, as illustrated in Fig. 4. Therefore, we believe that the incorporation of risk into maintenance management is essential.

3 Incorporating Risk into Reliability Centered Maintenance

We advocate the incorporation of risk management into RCM. In doing so, our aim is to develop a practical, yet sufficiently accurate method to add the dimension of risk to RCM. In this section, we will elaborate on this subject.

3.1 Risk Management

Before a detailed description of linking risk management to RCM is given, we will briefly explain the concept of risk-based asset management. As described in the introduction, international developments emphasized risk management as one of the key processes for asset management decision-making [10, 11]. Risk management comes down to a framework on how to identify and assess the consequences of events in terms of the key business values of companies and to compare these identified corresponding risks in order to prioritize risk treatment measures (accepting, mitigating or reducing risks). Risk is defined as the product of the probability of an event and its consequences [12, 11]. Generally speaking, the existence of risks implies that there is at least the possibility of negative consequences or deviations from expected values when an event has a probability to occur. Essential for risk management is that it is not just limited to solely technical risks of the network utility, but also extends to the management of risks involving the analysis of events for a complete system (i.e. organization, network, asset, etc.) that might have a negative impact. Moreover, the management of risk involves the decision-making process of measures to treat risks and the evaluation of these measures.

In such a socio-technical business model, the corporate mission, vision and strategy are connected to overall corporate business values. Although every network utility may develop unique business values, some generic, and widely adopted, business values are:

- Quality (customer minutes lost/worst served customer)
- Safety (injuries to personal)
- Finance (financial consequences)
- Image (reputation)
- Compliancy (regulations and legislations).

To ensure objectivity of the risk analysis, the probability and consequences are first assessed separately and afterwards combined to form an assessment of the risk. For this purpose, a two-dimensional risk assessment matrix is used to categorize the priority of each evaluated risk. After the risk assessment, the next step is the treatment of the risk, namely the determination of alternative solutions to deal with the risk. Dealing with the assessed risk can include decision such as accepting the current risk, take an action and invest in capacity expansions, maintenance, refurbishment, replacement or other operational procedures (i.e. restoration of outages, improved business processes, information system and data quality improvements, etc.).

Overall, risk management, as a regular business process, provides a method to identify, assess and treat an organizations risk to account for future events with a negative impact on the organization. Furthermore, it creates an awareness of socio-technical assessed risks and possibilities to treat them. Added to this, the application of an objective risk management approach provides network utilities to have control over risks and have a common language for sharing and discussing risks between management and engineers. It is also used to quantify and support arguments for budgets and portfolio planning. Network utilities use risk management for several aspects, for example, new investment projects, expansion investments, etc.

A well-known example of risk inspired maintenance analysis is RCM. RCM is principally focused more on safe risks, however in the following we develop a method in which other types of corporate risks, such as finance, are also incorporated.

3.2 Reliability Centred Maintenance

A sheer amount of literature is available covering the topic of RCM. The first industry to renew the widely-held beliefs about maintenance was the international civil aviation industry [13], where this framework is known as MSG-3 and outside this industry as RCM [14]. The method developed by Moubray [14] during the 1980s and 1990s was aimed to enable the retrospective application of RCM, which was initially rigorous and comprehensive [15]. This approach was widely acknowledged to form the basis of applications in other industries. As we are going to discuss the application of RCM outside its initially intended context, it is essential to point out that this needs careful consideration. In the civil aviation industry, for what RCM was principally designed, any failure would be unacceptable and failure modes should be designed out. If this would be impractical or uneconomic to design out, then a RCM regime was introduced to manage and mitigate the failure modes. When the interest of RCM shifted to the railway, water and power utilities, the fundamental difference compared to that of the aviation industry lies in the focus upon managing, which is, in case of network utilities, the management of the number, severity and risk of asset failures to a level that is acceptable to corporate business values. Therefore, we carefully, in the form of a pilot project, developed a RCM approach in which our corporate view on risk management is explicitly incorporated. Apart from this, performing RCM provides a means to find a balance between the need to ensure acceptable reliability levels, while also keeping maintenance costs under control [16]. Traditional maintenance regimes hold onto procedures that were either devised resulting from asset failures, or from manufacturer's recommendations. In both cases, the devised methods are unlikely to have been set-up based on an evaluation process which recognises engineering experience and operating conditions in which the asset is performing [17]. RCM provides a formal and structured process to carry out a comprehensive review of maintenance requirements of each asset in its operating context. The central focus in RCM is that the perspective maintenance is not to preserve the asset for the sake of preserving the asset, but rather to preserve the system function. With RCM, a thorough understanding of asset failure modes, failure causes, likelihood of occurrence and effects is achieved. Ultimately, this understanding can be used to define a maintenance task that prevents or proactively addresses the potential cause of failures in such a way that the overall cost of performing this maintenance task is reduced.

A wide variety of application forms of RCM are available. Depending on the purpose of the RCM analysis a specific form can be used. This may range from a classical (comprehensive) approach to a more pragmatic approach which is less time consuming, because readily available information is used. In our approach, the RCM process includes the following steps for the system/components under consideration:

i. Identify function
ii. Identify functional failure
iii. Identify functional failure cause(s)
iv. Identify the effect of the failure
v. Identify the impact of the failure
vi. Select maintenance task
vii. Other measures.

These seven steps can be grouped into three main parts as follows:

i. Steps 1–4: Failure Mode and Effect Analysis (FMEA), which provides an initial Risk Priority Number (RPN) of the failure.
ii. Step 5: Failure Effect Categorization (FEC), which provides a method to categorize the failure modes according to their effect in a uniform way. This helps with selecting an effective and proper maintenance strategy in the next step.
iii. Step 6: Task Logic, which provides, on basis of the FEC, means to define a maintenance strategy for each failure mode. Maintenance strategies such as, preventive (scheduled) maintenance, condition based maintenance or run-to-failure can be selected.

Prior to applying the RCM process, there is a RCM project definition stage. In this stage, a RCM analysis team is assembled. In this team, the level of breakdown of the system under analysis is decided upon (i.e. system, components, sub-component level, etc.). This team can also be enlarged by a RCM facilitator and a dedicated software program to perform each of the above mentioned steps. Most importantly, this group will collect all available information of the candidate system and define the scope of the RCM analysis.

3.3 Risk Dimension into RCM

Before we explain how the link between risk management and RCM is established and how we have developed a method to incorporate this link, we will briefly elaborate what the preceding reason is for this link in maintenance management. Besides the fact, as mentioned in Sect. 2.3, that risk management is widely seen as a prevailing method for asset management decision-making, there are also other reasons risk can be and should be incorporated into maintenance studies. As mentioned earlier, RCM was developed by the U.S. commercial aviation industry. Risks were rather simply divided into criticality classes (i.e. safety, operations, economics and hidden failures). The reason for these straightforward criticality classes is found in the physically compact, redundant and specialized nature of aircraft systems [18]. These criticality classes, were, and still are, the essential categories for developing a safe, effective and economical maintenance plan. For large aircrafts the categorization of (possible) failures in the RCM process could be linked directly to risk (criticality) ranking, which made the application of risk fairly straightforward for this purpose. When RCM became interesting for others, especially for nuclear power industry, the four original criticality classes continued to work accordingly [18]. The reason for this was because the systems to which RCM was applied included mostly vital areas and omitting systems with low probability or where the effect of the failure was not severe.

When applied in other industries, such as process-, mining-, power and gas-, network industries, etc. the needs and problems of the types of systems are different and the aforementioned criticality classes approach falls short. The fundamental cause for this falling short lies in the fact that as RCM is applied more and more outside its original context, the range of probabilities and consequences of failures is becoming larger. At the same time, the consequences depend on wider business values, assets have multiple missions and, more importantly, large populations of assets are geographically widespread.

The RPN is a commonly applied factor for calculating the risks associated with potential failure modes identified during the FMEA. With the RPN, a numerical value is assigned to each of the following categories:

- *Severity* (*S*), which is a rating for the severity or consequence of each potential failure effect
- *Occurrence* (*O*), which is a rating of the likelihood of occurrence of each potential failure cause
- *Detection* (*D*), which is a rating of the likelihood of detecting the failure cause.

Usually, each of the above mentioned categories are rated, for each failure mode, on the basis of the analysis of the RCM team. For this, past experience and engineering judgements are used. The specific rating description, criteria and values are defined by the RCM team in order to fit the system under analysis. When the ratings have been assigned, the risk priority number (RPN) can be calculated as follows:

$$\boldsymbol{RPN} = \boldsymbol{S} \times \boldsymbol{O} \times \boldsymbol{D} \tag{1}$$

with the aid of the RPN, the link can be made between risk management (Sect. 3.1) and RCM (Sect. 3.2). By adopting the risk rating description, criteria and values used by risk management, each potential failure mode is assessed against the corporate business values. In doing so, the RCM analysis clearly aligns with the overall maintenance management process and is building on the principle applied in the risk management approach. This seems straight forward, however the contrary is true when applied in practice. There are, in general, three difficulties that need to be taken care of when implementing risk management into RCM. These are:

i. The important requirement of the overall group to accept the notion of *risk*.
ii. Data availability to extract required failure occurrences (probabilities).
iii. A (sufficiently) accurate procedures for calculating the Severity and Occurrence

The first difficulty is dealt with by including a risk analyst in the RCM analysis and clarifying the notion of risk to the whole group. Because of the difference in specialities and application of risk management, this can be an intensive and time consuming experience. It was important to stress the fact that risk is not only a theoretical tool, but has sufficient practical foundation for maintenance management analysis. The second difficulty is one which requires a pragmatic approach. It is indeed true when one states that the available data is insufficient to calculate failure probabilities individually or for populations of assets. Usually, this is true, as, traditionally, databases were designed to record asset failures and not failure modes for RCM-based analysis. With the right combination of asset experts, manufacturer knowledge, engineering judgment and scientific collaboration many failure modes and rough estimations of failure probabilities can be determined in a practical way. The first two difficulties can both be tackled with a practical, sufficiently accurate procedure for calculating the RPN.

This brings us to difficulty three. We found, when implementing (1), that there were shortcomings in the calculation procedure. An effect and a failure mode are considered to be directly related and therefore have the same probability of occurring (e.g. torquing of a bolt will lead to breaking of the bolt), but the consequence of an effect and its impact on each business value (*S*) depends on multiple variables and circumstances (e.g. position of the bolt, importance of the bolt, time of occurrence, presence of people, etc.). When multiplying *S* with *O,* we implicitly assume that the probability of the failure mode (*Ofm*) is the same as the probability of the resulting consequences and impact (*S*). This is not true for many practical reasons. For instance, the probability of the failure mode (*Ofm*) is based on component failure data or experience. However, the consequences of the failures can be different for each failure mode. At the same time, the consequences have an impact on multiple business values, which can also have their own likelihood of occurring. Therefore, it is important to note that the probability of a failure mode (*Ofm*) is not necessarily equal to the probability of a consequence happening for a specific scenario (*Oscenario*). We would like to stress here that the identified failure mode will not necessarily lead to a maximum effect. In other words, the discovered effect may have consequences in different degrees (scenarios) each with its own likelihood (probability). In addition, the probability and impact of the effect, depending on the scenario, will be different for each business value. Only considering the "realistic worst case" consequences during the FMEA process will result in a one-sided view on the impact on the business values and will be prone to scepticism. Also, sometimes the consequences in a more likely scenario have a bigger impact on the business values than the worst case scenario due to the higher rate of probability. Which is why, we introduce an extended version of formula (1) in order to assure a (sufficiently) accurate procedure. In this extended version, two scenarios (worst case scenario and most likely scenario) for each failure mode are employed. Each scenario can, by itself, have an impact on the effect of multiple business values. Notably, it should be clear that the probability of the effect will vary for each business value within the scenario. The above mentioned description is made clear by means of a conceptual overview in Fig. 5.

This brings us the extended version of formula (1), which has been used in our practical application.

$$\boldsymbol{RPN}_{\boldsymbol{worst\ case}} = \boldsymbol{S}_{\boldsymbol{business\ value}} \times \boldsymbol{O}_{\boldsymbol{business\ value}} \times \boldsymbol{O}_{\boldsymbol{failure\ mode}} \times \boldsymbol{D} \tag{2}$$

$$\boldsymbol{RPN}_{\boldsymbol{most\ likely}} = \boldsymbol{S}_{\boldsymbol{business\ value}} \times \boldsymbol{O}_{\boldsymbol{business\ value}} \times \boldsymbol{O}_{\boldsymbol{failure\ mode}} \times \boldsymbol{D} \tag{3}$$

To illustrate the use of formulas (2) and (3), a simple example is given:

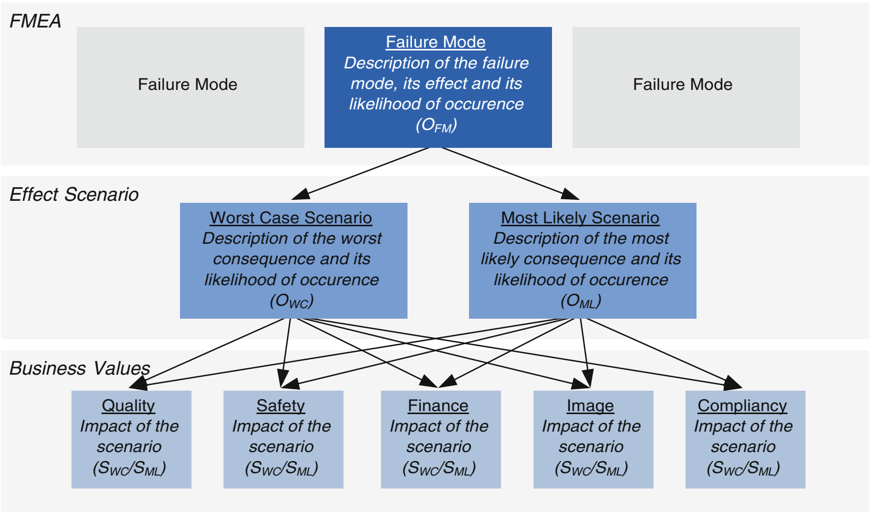


Fig. 5 Shows the interrelated issue with multiple business values for two effect scenarios for an identified failure mode

The probability of the scenario ($O_{business\ value}$) *and the probability of the failure mode* ($O_{failure\ mode}$) *together form a conditional probability* (*in parenthesis in formulas* (2) *and* (3)*. This conditional probability is then looked up in a table specifically designed for the calculation of the RPN. For instance,*

- $O_{failure\ mode}$: *probable* = 0.1
- $O_{business\ value}$: *probable* = 0.1
- *Conditional probability* = 0.1 × 0.1 = 0.01
- *In the table* (*risk management table*) 0.01 *is ranked as having a value of* 5
- *The value for the conditional probability is* 5 *and this will be used for the further calculation of the RPN value.*

Formulas (2) and (3) are used to calculate the RPN's for a total of 10 times (each scenario has 5 business values). Surprisingly, we experienced that for some particular failure modes, it happens that the overall RPN for the most likely scenario is higher compared to the worst case scenario. This lies in the fact that the impact in the worst case scenario may be more severe, however the likelihood of that impact occurring might be lower than for the most likely scenario.

When the RPN's are calculated, each failure mode can be individually ranked from high to low risk. Moreover, the ordering of RPN's will provide a priority ranking for choosing maintenance tasks to mitigate and control the occurrence of failures. One particular challenge we experienced when discussing these calculated

RPN's is that these RPN's should not be seen as absolute values. Instead, they must be used in a relative way. The consistency in the analysis is more important than the actual correctness of the absolute values. Finally, it is desirable to revise the initial risk assessment based on the assumption (or the fact) that the recommended maintenance actions have been completed. To calculate revised RPN's, a second set of revised ratings of *severity*, *occurrence* and *detection* for each failure mode are multiplied. The *initial* RPN's can be compared to the *revised* RPN's. This offers an indication of the usefulness of certain maintenance actions and can also be used to evaluate the value to the organization of performing the FMEA. In addition, an assessment can be made of the implications on risk exposure when certain maintenance tasks are not performed (i.e. in case OPEX budget cuts).

4 Implications of Risk Incorporated RCM for a Maintenance Organisation

Our endeavour towards using the RCM method for improving the organizations maintenance management activities has provided us with an opportunity to develop an extended approach of RCM and to link this to our risk management principles.

With this in-company developed method, we have a powerful and pragmatic tool to our disposal to utilize within our RCM pilot project. Here, we will describe how such a methodology benefits the overall maintenance management organization. Maintenance should contribute to the overall business goal, which is to sustain and control assets performance within boundaries over their lifecycles. In Fig. 6, we illustrate how the developed approach, finally, blends into the operational, tactical and strategic level of the maintenance organisation. In principle, Fig. 6 indicates for each level of the organisation what input data is required to perform a risk linked RCM analysis. More importantly, it has shown how the results, in turn, benefit each level of maintenance decision-making. At the strategic level, the complete asset risk profile for each failure mode of the analysed system can be ranked from high to low risk. Accordingly, an initial RPN and revised RPN (after maintenance task has been considered) are available. At the tactical level, the FMEA analysis can be used as input for important performance indicators to track the asset performance of a group of assets. Subsequently, it forms the basis for increasing the opportunity to use condition monitoring and diagnosis methods for a specific dominating high risk failure mode. Perhaps, the most important implication of the feedback takes place on an operational level, where the current maintenance tasks can be revised with the new or updated maintenance tasks resulting from the task logic analysis. In the end, we believe that such a wide approach towards maintenance management will provide network utilities to assess existing maintenance strategies and develop advanced mixes of new maintenance strategies. The success of such a comprehensive approach towards maintenance professionalization can only stand when

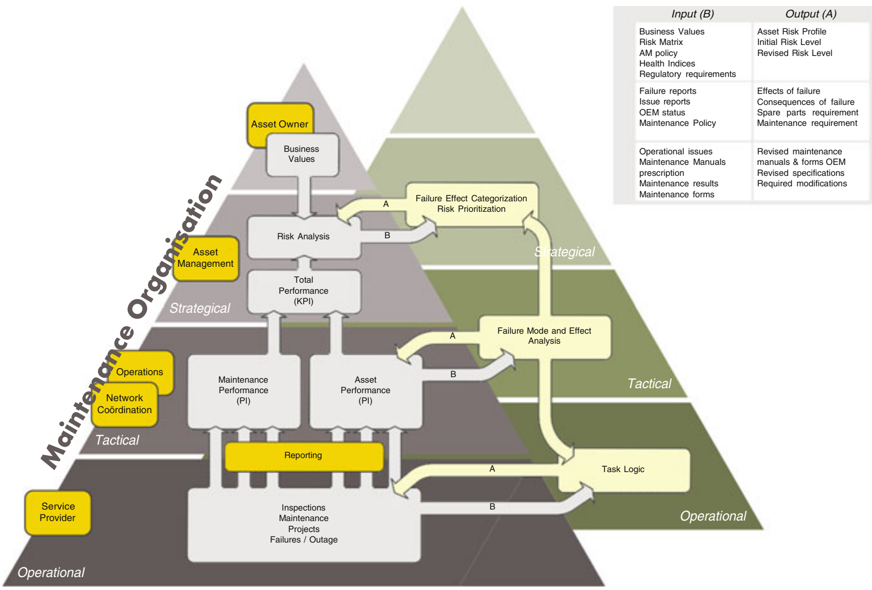


Fig. 6 The input and output from RCM linked with the overall maintenance organization is shown. From each level (operational, tactical and strategic) information is required to perform a solid RCM study. Nonetheless, the outputs from such analysis form an important source of information for predictable maintenance planning. Also, a list of the input and output information from a risk linked RCM analysis is shown

there is employee *and* management understanding and therefore we strongly encourage having a solid link of our developed method (or similar methods) with the overall maintenance decision-making process.

5 Case Study: Power Transformers

In this section, we will show how the developed method is applied in practice. Power transformers are one of the most critical assets in power systems due to their economic value and importance. Power transformers are used to transform the voltage down (or up) to distribution voltage levels. A power transformer consists of many sub-systems and equipment such as a cooling system, active part (windings and core of the transformer), tap changer, oil contention and preservation and bushings. Throughout the lifetime of a in-service power transformer, it undergoes various forms of ageing and degradation phenomena. A typical lifetime of a power transformer ranges from 45 to 60 years. We will elaborate on a case study for high voltage bushings (oil filled condenser type).

In recent history, a failure of a transformer bushing with above mentioned failure mode took place on a transformer of Stedin. Although the manufacturer of these bushings indicated this type of bushings as “sealed for life” and thus not refillable, we encountered in practice that due to degradation of gaskets, leakages are likely to occur. This type of transformer bushings does not have oil level inspections windows. If, due to leakages, the oil level is lower than a certain critical level, the occurrence of a short circuit will become inevitable. As shown in Table 1 (component hierarchy), the outer part of the bushing is made of porcelain insulation. In an independent failure report, it was reported that due to this failure mode (lower oil level in bushing) a short circuit to ground potential in one of the high voltages phases caused an explosion of the bushing with fire outbreak on the transformer as a result.

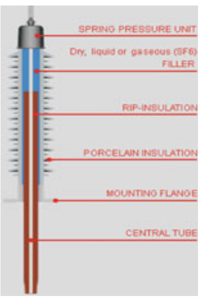
With the developed risk linked RCM approach, we now have at our disposal an analytical methodology to assess the impact of such a failure on each business value with an initial RPN calculation. Moreover, we can develop a maintenance (inspection or test) procedure for the whole fleet of transformers (∼200) with this type of bushings. Subsequently, with the aid of a revised RPN calculation, we have the ability to justify a revised maintenance strategy on the basis of risks which can be mitigated or controlled in a more proactive manner.

In Table 2, the results of the initial RPN calculation for both scenarios using formulas (2) and (3) are given. For each scenario, the RCM team agrees on a description of the possible impact. For this study, these scenarios are divided as:

- Worst case: *Power transformer burn, major injury, short article in local newspaper.*
- Most likely: *Transformer is switched off by protection, bushing explodes, burn damage on the transformer, transformer repairable, no injuries (nobody present).*

For this study, we have used the experience of the actual failure to make an estimation of the occurrence of the failure mode (1 time in 30 years). Currently, we have no detection measure for the failure mode and therefore the detection is ranked

Table 1 FMEA for high voltage transformer bushing

Component hierarchy	Function	Functional failure	Failure mode	Failure effect
	Provide an isolated connection between the transformer windings and cable termination	Short circuit between transformer tank and conductor	Low oil level, which can be caused by not on time filling or leakage due to a leaking gasket	Short circuit will lead to disconnection of the transformer from the grid. Loss of the bushing and possibility of fire

Source mosizolyator.com

Table 2 Improved RPN calculation for worst case and most likely scenario for the failure mode of Table 1

Scenario	$O_{failure\ mode}$	D	S and $O_{businessvalue}$	Business values				
				Safety	Quality	Finance	Compliancy	Image
Worst case	1 time in 30 years	No detection	Impact on business value (S)	Serious	None	Very serious	None	Small
			Likelihood of impact ($O_{businesvalue}$)	Possible[a]	–	Probable	–	Possible[a]
Initial RPN worst case				***70***	***50***	***300***	***50***	***50***
Most likely	1 time in 30 years	No detection	Impact on business value (S)	None	None	Serious	None	None
			Likelihood of impact ($O_{businesvalue}$)	–	–	Certain	–	–
Initial RPN most likely				***50***	***50***	***350***	***50***	***50***
Revised most Likely	1 time in 30 years	**Yearly inspection**	Impact on business value (S)	None	None	Serious	None	None
			Likelihood of impact ($O_{businesvalue}$)	–	–	Certain	–	–
Revised RPN most likely				***15***	***15***	***105***	***15***	***15***

[a] *possible* has a lower (10 times) rating than *probable*

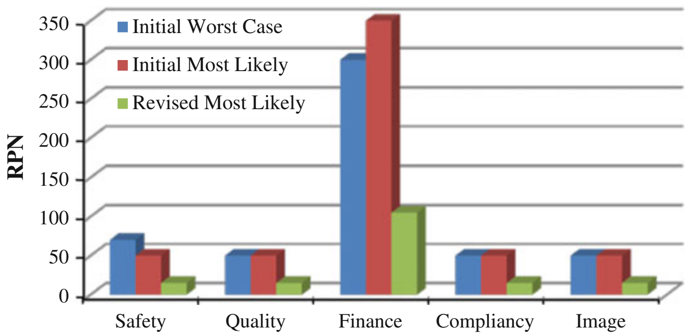


Fig. 7 Business value for initial (both scenarios) and revised RPN's

as no detection. For the severity and the likelihood of its impact, we have calculated the value with the RCM team as shown in Table 2. With the *Ofailure mode*, *Obusiness value*, *S* and *D*, the RPN's for each business value are calculated. The highest RPN is chosen and for this, a mitigating maintenance or inspection action is developed. For mere study purposes, we have developed an inspection task (yearly) for the oil levels of the high voltage bushing. The yearly interval was chosen because this can be scheduled in a practical way with existing yearly maintenance tasks. With the oil level inspection, the failure mode can be detected preventively. With this revised detection possibility, the revised RPN for the most likely scenario is calculated again and shown in Table 2 as well. In the appendix, more details regarding the calculation of the values of Table 2 are given.

In Fig. 7, the initial and revised RPN's are shown together. With this, the benefit in terms of business value risks for a maintenance or inspection task can be assessed. In practice, this developed tool is immensely benefiting the RCM team with preventing solely technical judgements to prevail the follow-up maintenance strategies. Moreover, we find that the technical experts are actually, gradually, developing an improved social-technical understanding of re-examining the traditional maintenance beliefs.

In the above discussed example, we have considered one failure mode for a high voltage power transformer bushing. However, for the complete analysis of failures of a system, this principle is applied to a whole power transformer as a system with its subsystems, components and parts.

6 Concluding Remarks

In summary, we stressed, in this article, the development of maintenance management and the importance of its continuous improvement and professionalization for power network utilities. Due to the large fleet of different assets, with different ageing, failure and maintenance characteristics, a maintenance management organisation needs to be established on proper processes, decision-making methods and systems. This will enable the achievement of suitable levels of maintenance organization maturity and service.

- Firstly, we described how Stedin has revisited its maintenance responsibilities and organisations.
- Secondly, with this as the basis, the company set out a growth development and made it clear and measurable for management levels with the aid of a maturity model.
- Thirdly, a pilot study was initiated with the aim to develop a practical, yet sufficiently accurate method for maintenance decision-making which should be founded on the principles of the overarching risk management model.

For this purpose, the principles of risk management are linked to the widely adopted RCM method. An expanded version of the traditional RPN calculation method has been introduced and extensively discussed in the article. Ultimately, we demonstrated how this method uses information from strategic, tactical and operational levels of the company. As output, and of vital importance, is the ability to assess the real contribution of maintenance to all these levels of the organisation. With the aid of a case study for power transformers, we have elaborated on the practical applicability of the developed tool.

It is expected that with this risk incorporated RCM analysis tool a structured framework is provided for analysing the functions and potential failures of assets, with the goal to develop a mix of maintenance plans that will provide an acceptable level of performance, with an acceptable level of risk against the corporate business values, in an efficient and cost-effective way.

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Human Resources Within ISO 55000—The Hidden Backbone to the Asset Management System

Lara Kriege and P.J. Vlok

Abstract This paper postulates that the human resource is the backbone of asset management systems. It is shown through review of literature that the five human resource areas (dealt with in this paper) are critical success factors to Asset Management. The management of human resources is often isolated within a single department, instead of being integrated into all functional areas of an organization, and this often diminishes performances in asset management activities.

Keywords Human dimensions · ISO 55000 · Asset management performance

1 Introduction

This paper sets out to emphasize the value of human resources (HR) within asset management (AM). AM enables an organization to achieve value from assets to realize its organizational goals. The asset management system (AMS) coordinates, directs and controls different asset management activities to achieve those objectives through AM. With ISO 55000 [24], an international standard for AM in organizations was developed to implement proficient AM in an organization and to build up a functioning AMS. It presents and describes several activities needed for the establishment of this system, which mainly include areas that affect the asset in a direct way. Practices that relate to managing the executing forces of tasks within AM are left out in the standard. ISO 55000 even sees this responsibility in another part of the company. This leaves the question of how important Human Resources is to an AMS and how much attention it should be given from the organization.

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J. Amadi-Echendu et al. (eds.), *9th WCEAM Research Papers*,
Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-15536-4_34

This paper distinguishes certain areas within HR, which directly influence the performance of an asset management system (AMS). A brief description of these areas will be given with their influences to Asset Management described. Furthermore, the criticality of these areas to the success of asset management systems will be shown. The above will thereby emphasize the importance of HR to Asset Management. Moreover, it will show how the lack of proper investment in HR can lead to detrimental effects on the performance of AMS, thereby concluding that HR can be seen as the backbone to asset management systems.

2 ISO 55000 and the Asset Management System

ISO 55000 represents the international standard for Asset Management within organizations. It was released in January 2014 and is based on PAS 55 [8], the first publicly available specification for the optimized management of physical assets, which was developed in 2004 by the Institute of Asset Management and the British Standard Institution (BSI). ISO 55000 focuses solely on the management of physical assets and describes factors that are important to generate value from assets in order to meet organizational objectives. The ISO standard is made out of three parts. While ISO 55000 states the general idea of asset management and an asset management system, ISO 55001 lists the requirements of the development, implementation, maintenance and improvement of an AMS and ISO 55002 provides guidelines for the application of AMS requirements described in ISO 55001.

This ISO Standard forms the basis for the implementation of an AMS within an organization. The purpose of an AMS as described in this standard is to direct, coordinate, and control asset management activities. This is to assure that assets perform as intended and achieve value to realize organizational goals as well as to reduce risk of failure. Different areas are embodied in the AMS, as for example policies, plans, business processes and information systems to ensure the delivery of asset management activities. Subareas and activities, which are referred to in this paper are:

- *Total Productive Maintenance (TPM)*, which describes a method for increasing production and reducing waste by permanently evaluating the condition of machines and processes. This helps assets to maintain performance levels as set by the organization.
- *Total Quality Management (TQM)* as one of the subject areas of the ISO 55000 standard to ensure assets meet performance requirements.
- *Enterprise Resource Planning (ERP)* as a tool, which organizations can use to keep track of, store and process information used within AM. This is true for fields such as condition monitoring that produces large amounts of data, which needs to be stored and analysed. ISO 55000 specifically calls for effective data management and transformation of data to information for measuring asset performance.

- *Defect Elimination*, which forms an integral part of quality management and therefore Asset Management. The defect elimination process often utilizes methods such as Six Sigma to plan pre-emptive actions.

ISO 55000 relates the above activities as well as others directly to the managing of physical assets. However, it does not consider the managing of human factors and personnel, which are of critical importance to these activities and to realize asset management objectives.

ISO recognizes the potential within the areas of leadership, culture, motivation, and behaviour in assisting an organization in achieving their asset management goals. In the ISO 55002 standard, it even emphasizes the importance of embedding AMS processes and activities into organizational functions such as HR where it also states the need of certain HR applications supporting the AMS. However, ISO realizes that an existing gap between important business processes and the AMS could lead to drawbacks in AM, it neglects their appearance within the AMS, and places their responsibility in another part of the organization [24]. Therefore it remains unclear to which extent and in what areas exactly HR is affecting the AMS.

3 Critical Areas Within Human Resources as It Pertains to Asset Management

Through literature review it has been discovered that there are five critical areas within HR that have a significant influence on AM and asset management systems. These areas are:

i. organizational culture
ii. motivation and leadership
iii. learning and development
iv. knowledge management
v. change management

Due to how influential these areas are to AM, they should be given an equal amount of attention. Furthermore, these critical areas interrelate with one another thereby creating dependencies on each other as shown in Fig. 1. The main link between an AMS and the HR areas appear with change management, knowledge management as well as learning and development. This is due to the active nature of these areas. Their application responds to events within Asset Management, while organizational culture and motivation and leadership take place more passively, as they usually refer to people's working habit. Organizational culture builds an overarching frame for the HR and AM fields. This culture is embodied through leadership and subsequently motivation. These two areas form a foundation for the remaining areas as well as Asset Managements, since they are critical to their proper performance. Knowledge management, change management and learning and

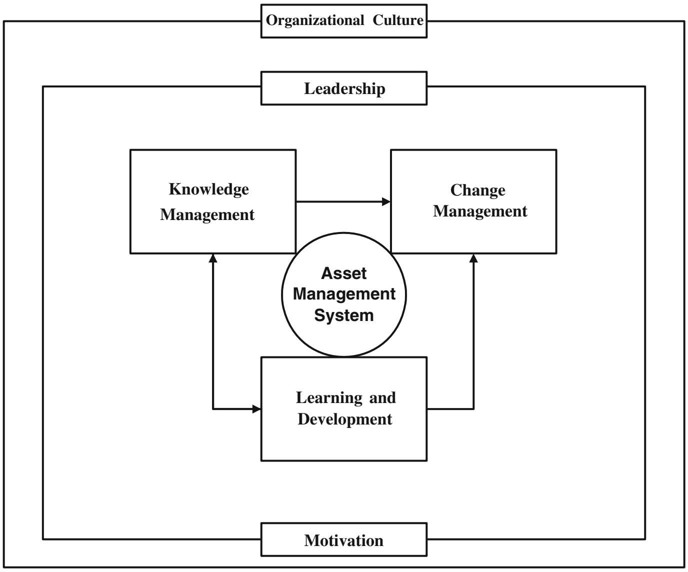

Fig. 1 Interrelations of human resource areas and an asset management system

development are those areas of HR that influence AM directly. Furthermore, they also interact with one another.

In the following sections these five areas are described, their importance to AM is highlighted and their interrelations with asset management systems are shown.

3.1 Organizational Culture

Armstrong [3] describes organizational culture as a configuration of values, norms, attitudes and beliefs that reflect in what way people are working and behaving in an organization. It reflects in every part of an organization and subsequently in asset management systems as well.

The foundation of an organizational culture is usually derived from the organization's vision and mission statement. They embody the values and purposes of a company and therefore guide employees' decision making. Values are the centre of an organizational culture, they describe beliefs and guidelines of how the organization and its people are supposed to behave and achieve the organization's vision. They are orientated around the organizational purpose as well as the personal values of organizational members. The people itself represent another main area of the organizational culture. It is important to match the persons to the organizational culture in order to create a consistent mind-set within the organization. In the end, the culture should be perpetuated somehow, giving employees as well as stakeholders the ability to refer to the organization's unique story [21].

Organizational culture plays a significant role in the implementation of the subject areas of Physical Asset Management. This is shown in a paper by [4], where it is stated that cultural dimensions, teamwork and respect for people are the most important factors when improving an existing Total Quality Management (TQM) system. Furthermore, organizational culture influences Total Productive Maintenance (TPM). Park [18] emphasizes this by stating:

> This research concludes that long-term benefits of TPM are the result of considerable investment in human resource development and management. For TPM practitioners, we advise to build a supportive culture and environment with a strong emphasis on human and organizational aspects to promote effective TPM implementation.

An organization needs to make sure that its employees fit the organizational culture and structure and that the tendency to compromise on the organization's values and vision is low. Organizational culture influences communication and the way knowledge is spread within the organization, the implication of successful changes, motivation as well as commitment to the company and therefore personnel turnover rates. Consequently, a lack of proper communication of values, norms, and vision between upper management and lower levels would have a relevant impact on productivity and work quality.

3.2 Leadership and Motivation

Several definitions of leadership exist, of which most include terms such as process, influencing, group and goal. Therefore, [17] defines leadership as a process in which an individual influences a group of people to realize a common goal. Leadership represents one of the most important areas of HR for AM, as the quality of leading, the performance of employees can be influenced significantly. For example, [25] considers leadership to be one of the most important success factors of Total Quality Management.

To describe how leadership works, [16] developed a concept of five levels of leadership where a leader is able to potentially reach five different levels, while he is always adding a new level to the one already achieved. The reached level relates to a certain relationship between the leader and the individual. This means that a leader is usually on different levels concerning different individuals. The goal for a leader should be to achieve respect from the people within his group. That is the pinnacle and thus the fifth level of leadership. The basis forms level one in which people follow the leader because of his position, because they have to. It is based on the leaders' right to lead, which however does not show real leading qualities. Group members in this stage are not willing to work over and above what is required of them. Level two refers to relationships between the leader and his group. In this stage, the leader receives the permission to lead and people follow because they want to. This is also where motivation plays an important role in improving relationships and to show people that someone cares about individual preferences. Level three is the production level; leadership is based on results. People will follow because of what a leader has done to the organization. In the fourth level, leaders reproduce their selves by developing the individuals in their group, in order to make them leaders as well. In this stage people follow because of what the leader has done for them. This follows the last and most challenging level, based on respect. Not every leader will reach this level. In this case, people follow because of who the leader is and what he represents [16].

Reference [7] identify the importance of leadership within AM as well, and discovered a positive correlation between TPM and top management leadership as well as human resources in general. These correlations are furthermore confirmed in a paper by [1], where they state that organizational leadership can significantly contribute towards competency within Total Productive Maintenance. Motivation is strongly related to the style of management and leadership and therefore is important to be mentioned here.

It can be describes as a set of forces that influence people to behave in a certain way. It gives the reason for doing something [3].

Motivation can be classified into two different types: Intrinsic and extrinsic motivation. *Intrinsic motivation* describes the reason for people to act in a specific way, because they feel inner satisfaction while doing so, rather than being incentivized by external factors such as pressure and rewards [21]. Work itself can be motivating, when people feel that the task is interesting, challenging or valuable.

Extrinsic motivation occurs when people are doing something in order to achieve a separable outcome. Extrinsic motivation factors can for example be incentives, higher pay, rewards, punishments or criticism. It can have a strong but usually short-term effect. Intrinsic motivation however is inherent in a person itself and has therefore a deeper and longer effect.

A lack of proper motivation and leadership can have serious negative influences on working attitudes and performance of people within asset management as well as within the whole organization. This emphasizes the importance that motivation practices should be anchored in the mind-set of managers and leaders in AM and therefore used constantly to receive high performance from employees. [5] found that next to other HR areas:

> Motivation of management and workforce is […] a key success factor in the implementation of TPM.

To achieve this, various motivation strategies exist, such as Maslow's hierarchy of needs and Herzberg's two-factor theory, which can be employed to support motivation within organizations. Furthermore, the way individuals feel connected to culture, how leadership is practised, as well as the opportunity to grow in terms of development in abilities and career will influence the impact of motivation significantly [3].

A crucial determining factor in motivating and leading subordinates is the ability to be empathetic and put oneself in their position. It is also necessary that managers take on the role of leaders by focusing on the individuals more and not solely on the task. This involves recognizing the individual accomplishments of employees and giving equal reward.

Poorly led and unmotivated employees will never work beyond their required performance and will never use their full working capacity, this is however necessary for effective asset management systems.

3.3 Learning and Development

Learning and development of personnel as part of Human Resources gives the organization the ability to achieve organizational objectives by developing employee's skills as well as offering individuals the opportunity to grow and develop for personal satisfaction.

Since the ISO 55000 standard as well as asset management in general is a rather new field in an organization, it especially requires a large amount of learning and development, in order to fully implement it into an organization.

Learning describes the process in which people acquire an enhancement in knowledge and skills. Development on the other hand makes sure that people progress from a present to a future level in understanding and capabilities that requires higher skills and knowledge. While learning and development lie in the range of an individual itself, training comes from the organization and can be seen as an element for learning and development [3].

Learning and development play an important role in today's organization as we are living in a knowledge economy in which knowledge productivity generates improvement and innovation of work processes, products, and services. This strongly relates to activities within AM, since ISO 55000 [24]:

> An organization's asset management system is likely to be complex and continually evolving to match its context, organizational objectives and its changing asset portfolio.

A subject area in which learning plays an important role in asset management systems is also for example in total quality management. Various References [2, 10, 23] state in their papers that training and learning are one of the major success factors for TQM.

Moreover, [13] argues that learning and development are no longer requirements for doing a job and improving performance, but integrated parts, which means that a job becomes more of a learning process with a need for high personal involvement of employees. Hence, the focus of learning and development should be shifted towards focusing on the individual itself, rather than on the organization only. Motivation is therefore a crucial factor for effective training and the learning ability of people [20], especially in the continuously evolving world of AM. This emphasizes the importance of managers and leaders to create a positive learning environment and to draw a link between learning activities and AM goals. If organizations however struggle to match these goals of learning outcomes with those of the employees' it can lead to significant losses in training effectiveness and consequently have negative impacts on project outcomes. A recurring problem with learning and development is the inability of an organization to recognize different learning capabilities and knowledge levels of individuals as well as proper justification for employees to participate. This indicates a lack from the organizational site in understanding effective learning strategies.

Andragogy, for example, represents one among many other approaches for learning and development in knowledge economies and describes key factors of the way adults learn [13]. The theory of Andragogy, as described by [14], highlights different aspects of adult learners. This includes, for example, the need for adults to know why they are supposed to learn something as well as the need to be autonomous to reach self-direction. Adults have a readiness to learn, which is strongly linked to their real-life situations. Furthermore, there is a need for orientation to learning in order to connect new skills and knowledge to these real-life situations. Another important factor is the need for motivation as without it, learning would be unsuccessful. An organization needs to make sure to understand aspects like these in order to achieve high outcomes out of learning and developing processes.

3.4 Knowledge Management

Knowledge management is seen as any process in an organization that generates, captures, shares and uses knowledge as a resource to improve learning and performance. While captures (storing) is concerned to integrate knowledge and expertise into computer systems, share (flow) describes the way knowledge is transferred. This can either be between individuals or from the individual to a database [3]. An example of knowledge flow from people to databases in the area of condition monitoring and maintenance within asset management systems involves for instance machinery breakdowns. Machinery breakdowns have to be resolved as quickly as possible, to ensure as little costs as possible for the organization. Consequently enough expertise needs to be available for repairing the machine. If however the person who has this expertise is not available, it is crucial to have access to his knowledge in terms of a database that contains instructions on solving this specific problem. If a breakdown occurs for the first time, it is then as important to share the knowledge of repairing the machine to ensure access by other people when needed.

This refers to the goal of knowledge management, which is the collection of all important knowledge and expertise that people bring into the organization and its distribution to where it is needed and where it can improve organizational performance [3].

It can be seen that TQM relies heavily upon knowledge management in addition to the aforementioned HR areas. Knowledge management is therefore as well an important factor of Total Quality Management as a part of ISO 55000 activities. This is for example shown by [6, 9, 23].

Two different kinds of knowledge exist and have to be managed: explicit and tacit knowledge. *Explicit knowledge* can be found in databases, intranet, documentation or other accessible sources within an organization. *Tacit knowledge* is however developed from personal experience and exists in people's minds and is therefore difficult to access. For wider use of knowledge in organizations, knowledge management has to find a way to transform tacit into explicit knowledge [19].

A major obstacle to proper knowledge management is the poor implementation of its processes and structures within an organization. This leads for example to ambiguous information and complicated protocols. Additionally, peoples' unwillingness to share information and knowledge further impedes a proper knowledge management system. In an accepted and trusted culture however, that highlights the need of knowledge sharing within the organization, people are more willing to share their knowledge with colleagues. The same relates to leadership, motivation as well as integrated learning and developing strategies. The right way of practicing it can lead to significant enhancement in the management of present knowledge and ensures that knowledge and information is available at the right place to the right time. A consistent and widespread knowledge management embodied into the AMS will speed up complex business processes and lead to faster results in asset activities.

3.5 Change Management

Change management represents a structured process in which change is realized in an organization by leadership to achieve a desired result.

Change management can be divided into two different types of change: Incremental and transformational change.

Incremental change in general is a change that takes place in an existing paradigm and organizational frame. It does not transform existing organizational structures fundamentally, rather it builds up on what is already achieved and involves changes in order to do things better.

Transformational change in the opposite includes changes to do things differently or to do different things. It does not stick to existing paradigms but often involves new organizational structure, culture and management [11]. Of the two types of changes, incremental changes are practiced more often than transformational changes.

An example for an incremental change within asset management systems is the introduction of a new, and more efficient way of handling a certain step of production. The difficulty in implementing new production steps is being able to convince the workers and to facilitate them in attaining the understanding of why it is important to execute this step in a different way. A problem in this case occurs, for example, when a new and young manager evaluates production processes and finds a more efficient way of doing a certain step. The executing workers, who have usually worked for the organization for a much longer period, often do not understand why the existing production step, which seemed to be the most efficient way over many years, needs to be changed and therefore do not accept performing it in the new way. This is especially the case when losses in pausing time or comfort accompany it. While this example illustrates only a small change, affecting few people and a small part of asset management, it still shows the importance of active and consequent Change management in order to fully implement the change.

An example of a transformational change might be the implementation of an Enterprise Resource Planning (ERP) system, which is an integral part of an AMS. Organizational processes and structures need to be revised in order to fully implement the new software. Reference [12] emphasize that organizational resistance to change management programs is a very critical success factor within the implementation of an ERP system.

To ensure that especially major changes like this example can be successfully implemented into an organization, it is important to understand the different stages for leading change and to take the right actions in each stage [15]. The Process can be divided into the following eight stages:

- *Establishing a sense of urgency*: Convincing and motivating managers to let go of the status quo and that the unknown will be better.
- *Form a powerful guiding coalition*: Building a team outside of normal hierarchy, which has enough power and commitment to direct the process.
- *Create a vision*: Developing a vision that guides the change and can be communicated to people affected by the change.
- *Communicate the vision*: Using every possible way of communication so that everyone affected by the change hears it repeatedly and using guiding coalition as example of new behaviour.
- *Empower others to act on the vision*: Removing structures that do not support new vision and support untraditional ideas and activities
- *Plan for and create short-term wins*: Rewarding people contributing to improvements in order to preventing people to lose sense of urgency for change.
- *Consolidate improvements and produce more change*: using early wins to produce more change by introducing more structures that strengthen the transformation vision.
- *Institutionalize new approaches*: expressing how change has influenced performance until it is fully integrated in the organizational culture.

If this is not given, the implementation of changes can go disastrous wrong and lead to major impacts on the success of Asset Management.

4 Conclusion

The highlighted areas of Human Resources in this paper give the reader a balanced overview about the HR areas that influence Asset Management and asset management systems the most. Even though HR is not the only cause of failure in asset management systems, it is clear from this article that deficiencies within Human Resources can lead to detrimental impacts within existing asset management systems. These deficiencies arise from poor implementation and a lack of understanding of the importance of HR and its strategies. Therefore, by rectifying these deficiencies it is possible to not only remove these detrimental impacts, but also to improve the AMS and to yield better performances. This indicates that Human Resources is indeed the backbone to the asset management system. It ensures the efficiency and productivity of the people that are the executing forces within the AMS as well as the other parts of an organization.

This mind-set however has not yet arrived in all organizational structures and processes and HR is often overlooked or generalized. HR cannot be seen as an isolated part with centralized responsibilities in the HR department. It needs to be integrated into the AMS itself as well as in all other areas of an organization.

To close this existing gap between practices of HR and the AMS, it is in an organization's best interest to invest both, time and money into improving their existing HR system. HR strategies need to be known and used by all leaders and managers in order to enhance business processes. However, it is also important to understand how the single areas of Human Resources interact with each other. As shown in this paper, it is never only one area that acts as a critical success factor to asset management systems. These HR areas always act together, influence each other and therefore can reach greater positive effects on AM performance if handled correctly.

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